A Numerical approach for Ship Energy Analysis

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Preface

This is a Master´s Thesis written at the Geophysical Institute at the University of Bergen. The work represents the end of a Master in Renewable Energy. The aim of this project has been to develop a tool and a method for ship energy analysis including emissions, efficiency and costs. The complexity of the tool made it necessary to cooperate with several sponsors and partners.

Researcher Tjalve Magnusson Svendsen from Prototech AS has been the man supervisor for the student through the project. The results are a product of a close cooperation between the student and Mr. Svendsen. The student is grateful for all the help provided, and for the understanding and advises given through the two semesters. Without Mr. Svendsen the result would not have been what it is. Many thanks to Tjalve Magnusson Svendsen and Prototech AS.

Professor Peter M. Haugan from Geophysical Institute has been supporting the project as a co-supervisor through the two semesters. Peter has been a supportive contributor for the results presented. Mr. Haugan has also been very helpful in arranging the study trip to Tokyo and giving advises in report writing. Without Mr. Haugan the result would not have been what it is. Many thanks to Peter M. Haugan.

R&D Manager Kristian Voksøy Steinsvik from Havyard Design & Solutions AS has been supporting the project as the second co-supervisor. The student had the pleasure of spending several periods in Havyard´s offices to cooperate with Havyard to develop the tool. Mr. Steinsvik has also been a key partner in developing the method used in the tool by advises and support. Without Mr. Steinsvik the result would not have been what it is. Many thanks to Kristian Voksøy Steinsvik.

The University of Bergen has provided help, support and advises for the project since the beginning. Several professors, scientists and engineers currently working for the Geophysical institute has been willing to answer question, share knowhow and give advises to the student. Senior Executive Officer Elisabeth Aase Sæther has been very helpful during the two years at the university. The student is really grateful for the two years he has been student at the Geophysical Institute at the University of Bergen.

The BKK-UiB cooperation has supported the project with 50 000 NOK. Without these funds, much of the work in this master´s thesis would not have been possible. In addition to the 50 000 NOK from the BKK-UiB cooperation, Hordaland County Council has supported the project with 9000 NOK. The student is very grateful for the funds granted from these two contributors.

Havyard Design & Solution AS has also been supporting the project with advisors, data, technical equipment and funds for travelling. Many thanks to the management in Havyard Design & Solutions AS for all help and support during these two semesters.

Norsk Fisketransport AS allowed the student to spend 10 days onboard the Live Fish Carrier NFT Steigen. The generosity of Norsk Fisketransport AS and the excellence and hospitality of the crew on board NFT Steigen helped the student improve the method and the tool. It was 10 educational days in good company. A special thanks to Captain Kent Sjåvik for being service minded, hospitable and willing to answer questions.

There are so many people involved in this project, and all of them have played an important role in the end results. It is not possible to thank everyone, but the most important involved persons will be given credit to underneath.

Lars Kolle, author of the book *"Håndbok for prosjektering av brennstofføkonomisk fartøy"* donated the student a copy of the book. Many thanks to Mr. Kolle for his generousity.

Assistant Professor Svein Anond Anondsen donated the book *"SIN 0501 - Marin Teknikk 1",* which played an important role in the ship design part of the tool. Many thankts to Mr. Anondsen and the Norwegian University of Science and Technology.

Director of Sales and Key Account Roger Rosvold and Vice President, Technology, Geoff Crocker from Corvus supplied the project with data from their battery systems. Product Manager Energy Systems Michael Odland from NES also helped the project with data from battery systems including efficiency and cost-estimates. VP Business Solutions Arnstein Wreime has supplied the project with data from Pbes battery solutions. Many thanks.

Area Sales Manager Johanna Wreime, Senior Sales Manager Dirk Folchert and Product Manager Pål Erik Ruen has shared knowlegde and data from Rolls-Royce, Wartsila and PonCat. Without data from these suppliers the tool would never be as precise as it is. Many thanks.

Business Manager Johan Burgren from Powercell Sweden has been willing to share performance data from Powercell AB´s fuel cell technology. Business Development Manager Mark Kammerer has shared data and knowledge from Hydrogenics GmbH with the project. Many thanks.

The student is really grateful for all the help provided by the contributors mentioned above. All data are used to estimate performance and costs for engines and batteries in the tool. This makes the tool state-of-the-art and representative for modern technology.

Bergen, 2018

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Abstract

This master´s thesis has focused on energy analysis of ships and ship designs by developing a tool and a method for numerical analysis for evaluation of emissions, efficiency and costs. The overall focus has been on making the tool simple and understandable for the concerned user. This has been done by combining simple inputs filled in by the user and advanced inputs by predefined, editable values. The tool has been tailored for a passenger vessel, a live fish carrier and a double-ended car ferry but can also easily be modified to other vessel types such as offshore wind vessels and bulk carriers.

The tool is presenting CO_2, NO_x, CO, PM and SO emissions as well as carbon footprint from combustion and production of fuels. Lifetime costs estimations for the systems analyzed in the tool are also included. Diesel, LNG, Hydrogen and batteries are energy carriers analyzed in the tool. The tool also provides a mean for comparing different powertrains and energy carriers at an early stage of a design process, in order to select the best available concept and/or to possibly exclude some of the powertrains evaluated, before entering a detailed design phase.

It is developed a methodology where the four disciplines *ship design, route studies, engine setup* and *costs* are included. By adding precise values for selected inputs in the four disciplines the result is expected to be relatively exact. The relative difference between the engines studied are in order with the market trends.

The tool and results have been compared with observations made onboard NFT Steigen in Vestfjorden, Norway February 2018. A study trip to Tokyo, Japan has played a role to the master´s by observations and data collected. The amount of data collected from the industry used to present state-of-the-art engine curves has made the tool modern and representative for new technology.

Batteries are found to be the 40% cheaper and 57% more efficient than diesel engines for double-ended car ferries operating shorter crossings along the Norwegian coast. By use of the tool it has also been shown why batteries are less favorable for cruise ships and live fish carriers due to charging time, costs and weight. This report does not include studies or discussions of availability of materials used in batteries or limitation of production.

Hydrogen still face challenges regarding several factors such as infrastructure, rules and regulations, costs, availability and public awareness. The tool can be used to analyze the effect of cost reductions of fuel cells and hydrogen and improved efficiency. By doing this, it has been shown that hydrogen can compete with traditional fuels such as LNG and diesel in the future. By use of hydrogen produced from renewable energy, the carbon footprint from hydrogen can be kept low.

To ensure that the tool stays a state-of-the art aid for analyzing ship emissions and efficiency, the data and content has to be constantly updated. Several add-ins such as rest-heat-recovery, carbon footprint from production of engines and an engine optimization tool will, if added to the tool, improve the tools functionality.

Samandrag

Oppgåva har fokusert på energianalyser for skip og skipsdesign ved å utvikle eit verktøy og ein metode for numerisk analyse av utslepp, effektivitet og kostnad. Fokuset har vore retta mot å sette saman eit verktøy på ein enkel og brukarvennleg måte. Ved å kombinere enkle innstillingar som brukaren sjølv må fylle inn og avanserte innstillingar som er førehandsinnstilte men moglege å endre har verktøyet vorte handterbart for brukarar med meir eller mindre erfaring innanfor fagdisiplinane. Verktøyet har vorte skreddarsydd for eit passasjerfartøy, ein brønnbåt og ei ferje, men kan også lett modifiserast til bulkskip, offshore-vind fartøy og fleire.

Verktøyet reknar ut CO_2-, NO_x-, CO-, PM- og SO-utslepp. Det finn også karbonfotavtrykket frå produksjon, transport, mellomlagring og forbrenning av dei ulike drivstoffa. Levetidskostnadar er også utrekna. Diesel, flytande naturgass, hydrogen og batteri er dei fire energiberarane som er inkluderte i verktøyet. Dette er også eit grunnlag for å samanlikne forskjellige energioppsett og energiberarar tidleg i designprosessen, for å best kunne velje det mest ideelle konseptet og/eller om mogleg å kunne ekskludere nokre av alternativa, før ein går vidare i detalj-prosjektering av skipet.

Det er utvikla ein metode der dei fire disiplinane skipsdesign, rutestudier, energisystemoppbygging og kostnad er inkludert. Ved å legge inn eksakte verdiar for innstillingane er det forventa relativt eksakte resultat. Den relative skilnaden mellom dei forskjellige energisystema stemmer også overeins med dei forventa trendane i moderne energiteknologi.

Verktøyet og resultata har vorte samanlikna med observasjonar gjort om bord på brønnbåten NFT Steigen i Vestfjorden, Norge i februar 2018. Ein studietur til Tokyo, Japan utført oktober 2017 har også spela ei viktig rolle for utviklinga av verktøyet gjennom observasjonar og datainnsamling. Mengda av data samla inn gjennom industrien for å anvende moderne effektivitetskurver har gjort verktøyet moderne og representativt for nyare motorteknologi.

Batteriteknologi har vist seg å vere 40% billegare å 57% meir effektivt enn dieselmotorar for bilferjer i operasjon langs Norskekysten i følgje verktøyet. Ved å bruke verktøyet, har ein også vist at for eksempel brønnbåtar og cruiseskip vil ha utfordringar med å nytte batteri grunna ladetid, kostnad og vekt. Rapporten inkluderer ikkje studiar eller diskusjonar rundt materiale som er viktige for å produsere batteri, og kor vidt denne produksjonen er berekraftig eller ikkje.

Hydrogenteknologi har framleis ein veg å gå når det kjem til infrastruktur, reglar og retningslinjer, kostnad, tilgjengelegheit og allmenn aksept. Verktøyet kan verte brukt til å analysere effektane av kostnadsreduksjonar for brenselceller og hydrogen og forbetra effektivitet. Ved å gjere desse analysane har det vorte avdekka resultat som indikerer at hydrogen kan konkurrere med tradisjonelle drivstoff. Ved å anta at hydrogen er produsert ved fornybarteknologi, får ein også eit relativt lågt karbonfotavtrykk.

For å sikre at verktøyet opprettheld sin status som moderne og representativt må datasetta regelmessig oppdaterast. Forskjellige tilleggsfunksjonar som restvarmeutnytting, karbonfotavtrykk frå produksjon av energisystema og eit motoroptimaliseringsverktøy vil kunne gjere verktøyet endå meir funksjonelt.

Content

Nomenclature

Explanation	Conception
Air-Fuel Ratio	AFR
Beginning of Lifetime	BoL
Brake Power Efficiency	BPE
Carbon Capture and Storage	CCS
Carbon Monoxide	CO
Carnot Heat Cycle	CHC
Carnot Heat Engine	CHE
Combined Gas and Steam Turbine	COGAS
Compressed Natural Gas	CNG
Compression-Ignition	CI
Computational Fluid Dynamics	CFD
Diesel Oxidation Catalyst	DOC
Diesel Particle Filters	DPM
Electromotive Force	emf
End of Lifetime	EoL
Energy Efficiency Design Index	EEDI
Graphical User Interface	GUI
Hybrid Internal Combustion Engine	HICE
Hydro Carbons	HC
Internal Combustion Engine	ICE
International Maritime Organization	IMO
Lean NO_x trap	LNT
Liquid Natural Gas	LNG
Molten Carbonate Fuel Cells	MCFC
Nitrox	NO_x
Norwegian University of Science and Technology	NTNU
Otto Cycle	OC
Particular Matter	PM
Phosphoric Acid Fuel Cells	PFC
Proton Exchange Membrane	PEM
Rotate per minute	RPM
Rotations per minute	RPM
Selective Catalyst Reduction	SCR
Solid Oxide Fuel Cell	SOFC
Spark-Ignition	SI
State of Health	SoH
Stoichiometric Diesel Compression	SDC
The Marine Environment Protection Committee	MEPC
UIB	The University of Bergen

1. Introduction

In the following introduction, the targets and thoughts behind this master´s thesis are discussed. The motivation, the idea and the way the project was ran, are presented. A hypothesis for the result of the project is also presented.

1.1. The Idea

The increased focus on emissions and efficiencies makes it necessary to learn more about ship designs, consequences of choice, potential reductions in emissions and cost of power systems for maritime applications. In this project, a method-based tool to evaluate emissions, efficiencies and cost of different systems for powering ships has been developed.

This tool is briefly an energy analysis based on emissions and efficiency. To give a representative outcome of variables used in the tool, four different disciplines were evaluated as shown in Figure 1. One of the questions asked were how these variables affect each other. Choosing the most thermodynamic efficient engine will not necessary result in the most thermodynamic efficient ship design. The *harmony* between the variables were an important question in this research. Was it possible to make a generalized tool with exact results?

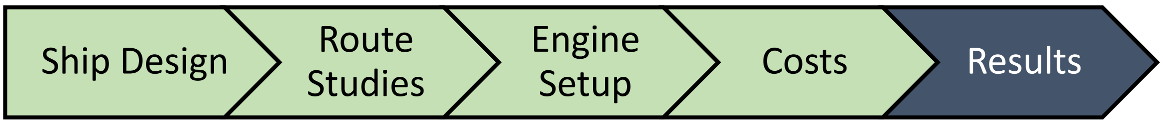


Figure 1 The Project Process and the necessary disciplines included in the tool.

This project has developed a method based on previous research regarding similar research question. Two examples of this is "*Utslippsfri båtrute I Oslofjorden – Forprosjekt*" by LMG MARIN, 2017 [1] and *«Energieffektiv og klimavennlig ferjedrift»* by Statens Vegvesen [2]. Theory from official published literature and know-how from the maritime cluster and Havyard Design and Solutions have been of great use in this project.

The tool will have to use state-of-the-art data as pre-defined variables for the analysis. It was expected that the project would face challenges gathering data due to confidentiality. Therefore, all inputs represented by the disciplines in Figure 1, would have to be editable.

To optimize the tool to give the most representative result, three versions were designed. One for a cruise ship operating "Kystruten Bergen-Kirkenes" along the Norwegian coast hereby described as the passenger vessel, one live fish carrier and one double-ended car ferry. The tool can easily be modified and used for offshore wind service vessels, bulk carriers and other types of ship designs.

The project was also supposed to give an overview of drawbacks and obstacles for introducing renewable power systems for ships sailing among the Norwegian Coast and on the Norwegian Continental shelf. By looking into possible scenarios for cost- and technology development, hydrogen and batteries were discussed as possible energy carriers for the three ship types in the future.

1.2. Motivation

Through endless time, ship transport has been a major contributor to trade all over the world. Since the development of the diesel engine, the research has been contributing to increased efficiency and decreased emissions.

When the Paris Agreement achieved the threshold for entry into force on October 5th, 2016, 160 parties agreed upon a global agreement to reduce global warming. "*The Paris Agreement`s central aim is to strengthen the global response to the threat of climate change by keeping a global temperature rise this century well below 2 degrees Celsius above pre-industrial levels and to pursue efforts to limit the temperature increase even further to 1.5 degrees Celsius.*" [3]

Every country signing the Paris Agreement agrees upon a common list of actions to consider in their climate goals. For global emissions to peak as soon as possible, ambitious targets will be set to make politicians in each country struggle for environmental friendly solutions. Every fifth year, the countries in the Paris Agreement should meet to agree upon targets that are even more ambitious. Each country will report on how well they are doing on reaching their targets, and track progress towards their long-term goals. [3]

The Paris Agreement made a difference globally since it forces countries to set their climate targets and share them with the other parties in the agreement. Since transport in general is a major contributor to global emissions, countries will have to look at the exhaust gasses from transport sectors as a possible area to cut emissions.

Not only does the Paris Agreement make countries focus on emissions and global warming, but also energy efficiency. Since all the contributors are obligated to report their goals and achievements, it forces decision holders to point at all sectors using energy. This will make investors and decision holders in shipping increasingly focus on efficiency and emissions.

A report produced for The Norwegian Ministry of Finance in 2015 [4], documents which sectors contributing the most to greenhouse gasses emissions in Norway (Figure 2 also includes sectors outside the carbon quota system). Domestic shipping and oil- and gas industry represents a significant part of the emissions.

According to *International Chamber of Shipping* [5], global transport of goods is by weight/distance done 90% by shipping. Even though most of the goods transported are sent by ships, shipping only represent 2.2% of the world´s total CO_2 emissions.

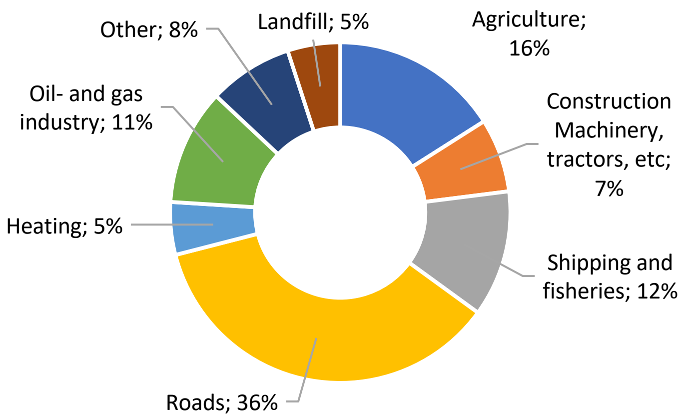


Figure 2 Contributors to greenhouse gasses for industries not regulated by carbon credits. [4]

Fossil Fuel Emissions account for about 50% of the global NO_x emissions. Shipping contributes to more than 10% of these emissions, according to M. G. Lawrence et al. [6]. The *International Maritime Organizations, IMO,* latest Nitrogen Oxides regulation (shown in Table 1), *Regulation 13 Tier 3,* states the total weighted cycle emissions limit for an engine. By satisfying these regulations, the ship achieves an Engine International Air Pollution Prevention Certificate for NO_x emissions [7]. Local NO_x emissions represent a threat to the local environment poisoning the air and potentially water resources nearby the emission source. In fjords and cities, there is a high focus on reducing the NO_x emissions.

Table 1 IMO Nitrogen Oxides Regulation 13. [7]

Tier	Ship construction date on or after	Total weighted cycle emission limit (g/kWh) n = engine's rated speed (rpm)		
		n < 130	n = 130 - 1999	n ≥ 2000
I	1 January 2000	17.0	$45 \cdot n^{(-0.2)}$ e.g., 720 rpm – 12.1	9.8
II	1 January 2011	14.4	$44 \cdot n^{(-0.23)}$ e.g., 720 rpm – 9.7	7.7
III	1 January 2016	3.4	$9 \cdot n^{(-0.2)}$ e.g., 720 rpm – 2.4	2.0

IMO introduced in 2011 the *Energy Efficiency Design Index,* which forces ship designers to increase ships efficiencies by 30% from a 2011 reference line [8]. The Marine Environment Protection Committee (MEPC) is the committee addressing environmental issues under IMO's remit. Currently the *EEDI* has to be implemented for ships above 400 GT, and exceptions are made for ships with electric, turbine or hybrid propulsion systems, which means that most ships design and built in Norway these days does not have to implement the EEDI.

All the new regulations and political discussions regarding environmental and efficient power systems for ships makes ship designers focus not only on emissions and carbon footprint of shipping, but also energy efficiency. This project will look into existing studies at energy efficiency and emission comparison studies for maritime applications and make an improved tool for energy design evaluation for modern ship technology. The tool will be discussed, tested and evaluated.

1.3. Hypothesis

The tool developed in this project was designed to be a comparison tool between different energy systems. The tool should be designed to be accurate and capable of analyzing emissions and efficiencies with potential of relatively low errors.

The hypothesis of the work, to be tested by using the tool, was that renewable energy system running any ship operating along the Norwegian coast or on the Norwegian Continental shelf could be cost effective compared to fossil fuel systems used in maritime applications today. It was expected that this could be possible using hybrid solutions with lithium batteries and hydrogen fuel cells.

It was expected that the tool designed in this project in the end works best as a pre-contract tool for indicative purposes, and that for more precise analysis, a proper design analysis would have to be made.

1.4. Previous studies

The increased focus on emissions and energy efficiency have made researchers and engineers focus on different zero-emission powertrains for maritime applications. Because of the rapid development of more efficient, cheaper and less polluting fuel systems of all types, using research older than 3-4 years may lead to wrong assumptions and less representative results.
A comparison study of a battery-, hydrogen- and diesel-powered passenger ferries in the Oslo fjord were published by LMG Marin I august 2017 [1]. Another study used as a reference in this master thesis is "*Energieffektiv og klimavennlig ferjedrift"* also made by LMG Marin and produced for *Statens Vegvesen* [2], a possibility study regarding environmental powertrains for car ferries operating in Norway. This master´s thesis has used information from both of the studies conducted by *LMG Marin*, but in addition produced an open access tool that can be used for decision holders deciding between different energy systems for different designs in a pre-contract phase.

1.5. Method

This master thesis focuses on developing a method for analyzing ships and ship routes. The project was based on a problem, and the theory study, method, discussion and results were all based on the problem to be answered.

In Figure 3, the problem was addressed hierarchically. By analyzing and evaluating the problem, the necessary theory study and research were evaluated.

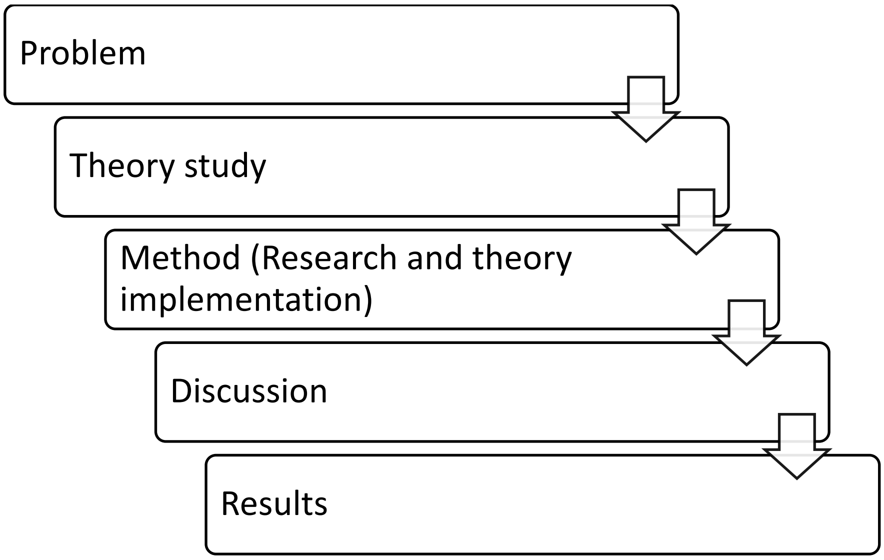


Figure 3 Method

Even though Figure 3 represents a hierarchically description of the project, there were a strong connection between implementation of theory and research in the development of the tool. During the construction of the tool, it was necessary to go back to the theory part to collect more data from past projects to complete the thesis, as shown in Figure 4.

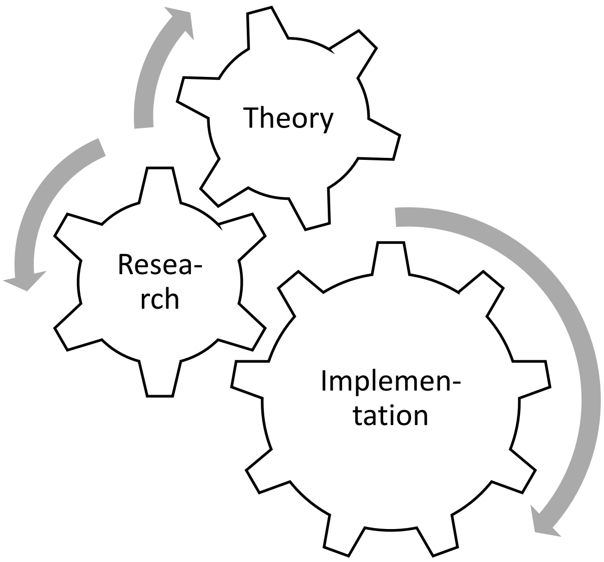


Figure 4 Theory and research mechanisms.

The first months of this work were mainly used for theoretical studies and review of previous studies. After the student had sufficient theoretical knowledge to start designing the tool, several suppliers of state-of-the-art technology and solutions were contacted to retrieve data used as a baseline for the calculations in the tool. Market trends, component online specifications sheets and etc. were used whenever data from suppliers was unavailable due to e.g. confidentiality. The tool was designed and developed for a double-ended car ferry, a live fish carrier and a small cruise ship (the passenger vessel) but can be used for other vessel types as for example offshore-wind vessels and transport vessels if minor modifications are made. A trip to Tokyo was also arranged to learn more about the effort made there to transfer energy production and consumption into renewable energy sources.

After the first design of the tool were completed, a field trip onboard the live fish carrier NFT Steigen were arranged. The purpose was to test the operational procedure with the theoretical suggestion the student had designed before the field trip. It was also important to learn more about energy consumption, awareness of use and different operations.

After the field trip, several months were spent to improve the design of the tool together with the supervisors Tjalve Magnusson Svendsen, researcher at Prototech AS, Kristian Steinsvik, R&D Manager in Havyard Group ASA and Professor Peter Haugan at the University of Bergen.

2. Background

To make a proper tool to evaluate the energy consumption for ships, different analysis and assumptions has to be made. In the following background section of the report, ship design theory, route studies, load dependent losses, fuel curves and fuel types, emissions and assembly and price will be studied in the order presented in Figure 5.

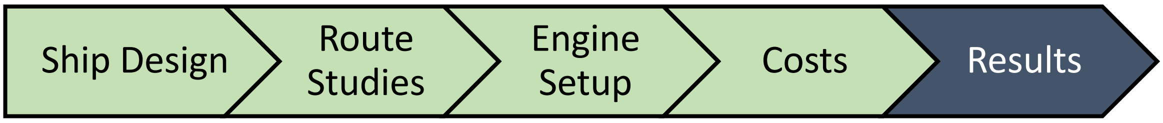


Figure 5 Hierarchically presentation of the sections in the theory chapter.

When a ship designer is handed a job, it often includes a specification of the scope of work the ship is going to do. It also specifies limitations and requests such as loading capacity or bollard pull. In addition to the specific construction demands, the ship designer should also consider the operations that the ship is doing. To be able to estimate the energy needed to operate the ship or to evaluate the powertrain, route studies has to be carried out.

In order to estimate energy absorption, fuel consumptions and emissions for the ship design, the designer need to consider powertrain efficiency and emissions. By using these inputs together with the ship design and the route studies, a fuel consumption for a given period can be calculated.

In the end the lifetime costs of the system can be estimated by calculating the fuel costs and the installation costs of the powertrain.

2.1 Ship Performance

It is useful to determine the resistance of a ship in water for given velocities. To find this relation can be a challenging operation and this master´s thesis will not go into advanced hydrodynamics to explain this. It will instead focus on a practical understanding of the design process and critical factors.

In this section, an overview of ship design theory is presented. The purpose is to introduce basic principles of ship design and which factors that have the biggest impact on the overall efficiency of the ship. An increased focus on these factors can contribute to a better environmental impact of the ship.

2.1.1 The design processes

The design-process is a complex process with different disciplines involved. There is no standard procedure for how a ship is designed and the method varies from ship to ship. Figure 6 shows the suggested design-loop in Havyard Design and Solutions AS [9].

There is always a trade-off between the different disciplines. An example of this is that a ship with more breadth may have better stability and a ship with smaller breadth may achieve better performance. To find the optimal trade-off in a design-loop the disciplines have to cooperate.

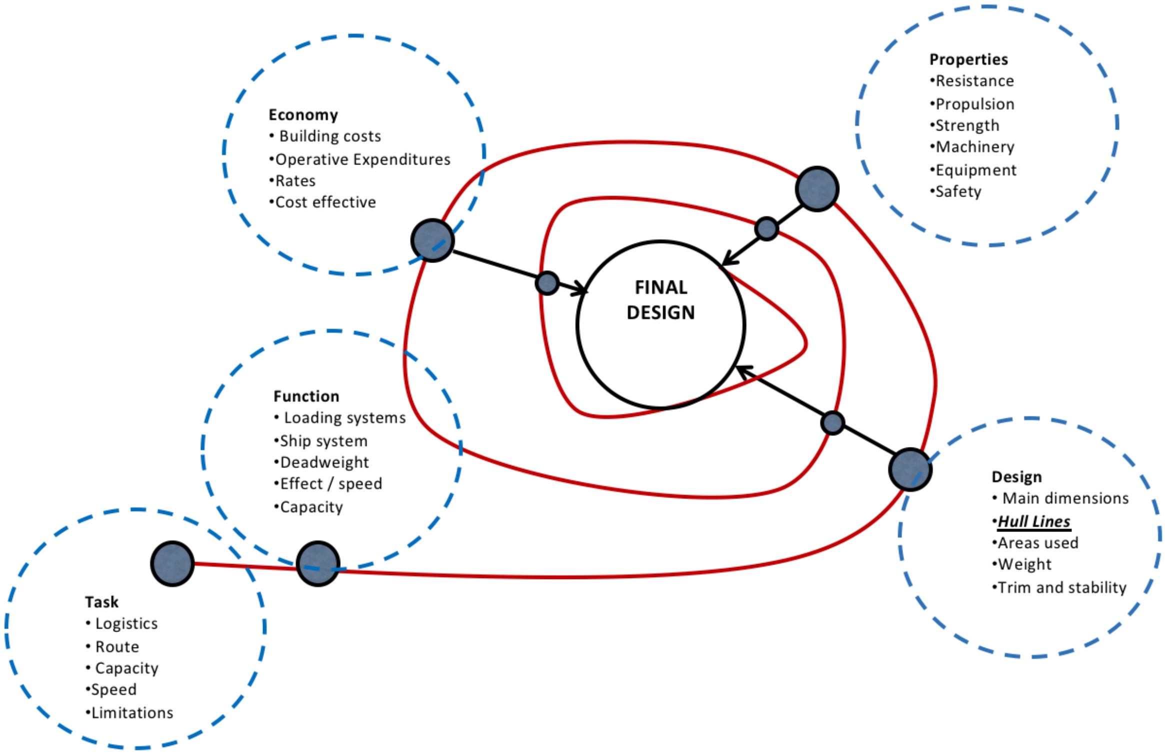


Figure 6 The design-loop [9].

In *"Håndbok for prosjektering av brennstofføkonomisk fartøy"* by *Norges Skipsforskningsinstitutt* several design steps are suggested to design a fuel effective ship. Compared to Figure 6 this is a simplified method. The steps suggested are described in sections 2.1.1.1-2.1.1.7.

In appendix G-H, some theory of calm water performance and ship size parameters can be found. This information is not used to produce the tool but useful information for the broad understanding of ship design.

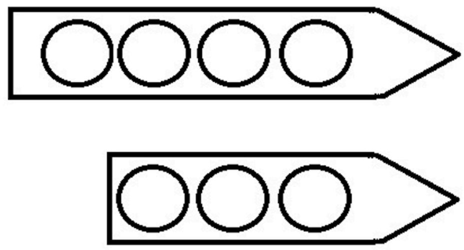
2.1.1.1 Capacity

Capacities can both be related to area, volume and weight. Some designs will be critical regarding volume and not weight and vice versa.

The Capacity of the ship is in many cases one of the criteria that influences the energy demand for ships most since it has a big impact on both the size and the weight of the ship. In most cases, the rest of the ship is designed around the capacity of the ship, since the unit amount in many cases also represents the purpose, which means that number of crew, necessary engine power and main dimensions are all dependent on the capacity. An example of a ship where capacity is less important can for example be diving vessels or other ships where equipment installed are more important than loading capacity.

One way to illustrate this is by drawing four circles on a row representing the fish tanks and drawing a rectangle around those four tanks, illustrating the fish tanks on board a *Live Fish Carrier,* as shown in Figure 7. This dimension represents the minimum dimension necessary to fit the requirements from the customer. In addition, the ship will need a bridge, an engine, a hotel and other facilities. By reducing the numbers of tanks from four to three, the length and weight of the ship reduces considerable.

Figure 7 Ship 1 with four fish-tanks and ship 2 with three fish-tanks.



"The requirements for a given capacity in m^3 of fresh- or sea-water used to transport live salmon gives the designer some choices regarding width, length and height on the fish tanks. When the tanks are defined, fore ship and aft ship are designed. In this process, different considerations have to be accounted for dependent on the customer`s requests and priorities. It is not necessarily the smallest dimensions around the defined capacities that gives the lowest absorptions." [10]

2.1.1.2 Speed

Every ship has its purpose either it is transport, fishing, etc. Every ship moves from A to B with a given speed. This speed is an important factor in dimensioning the power system. Dependent on the hull, a ship speed can be optimized dependent on hydrodynamic variables. The speed requested from the customer is not always the speed that is agreed upon as the optimum in the building specification. The speed request is anyhow an important parameter that has to be considered when designing the ship. In 2.1.3 Formula 8 presents the relation between the resistance components for a ship, namely *the towing resistance*. In addition to the towing resistance comes the propulsion resistance [11].

2.1.1.3 Main dimensions

Given the speed requirements and the capacities, the main dimensions will be decided. This meaning length, width, height, depth and weight. It is important to find the ideal dimensions for the purpose of the ship

2.1.1.4 Hull shape and propeller

When the main dimensions and the required speed are decided, the hydrodynamic engineers use the data in a workbench doing CFD-analysis (Computational Fluid Dynamics).

The propeller has to be optimized for the given hull. In most cases, the propulsion system (number of propellers and type of propellers) are chosen by the ship designer, and the hydrodynamic design of the propeller blades are designed by specialists in that area.

2.1.1.5 Power system and energy flow

The Power system and energy flow is the part were the designer can choose between several engine types and powertrain build-up.

In the power system and energy flow stage, route studies, energy analysis and capabilities of the design are done. This is done to evaluate which energy system that suits the design. For a ship operating with large power peaks but in general a low average power rate, a battery stack can help reducing the size of the engine. By utilizing knowledge from other industries and evaluating alternative fuel types and hybrid solutions, emissions and consumptions can be reduced. This is a design phase with a critical impact on emissions and efficiency of the power train [12].

2.1.1.6 Maintenance

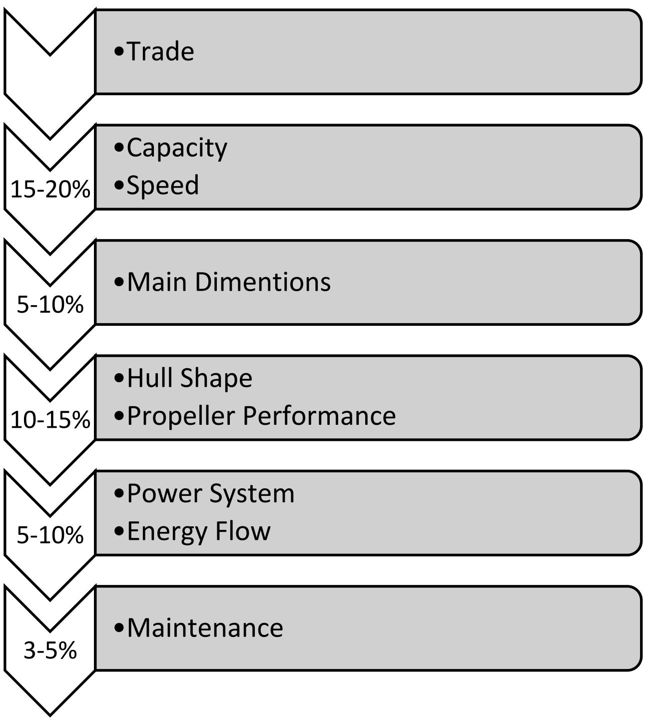
The last stage of the design phase is where the ship designer optimizes the maintenance procedures of the ship. Having a proper maintenance routine for the integrated systems onboard the ship, has a significant effect on the overall profitability of a ship's operation. The maintenance includes both internal adjustments on the engine and other power components of the ship through the ships lifetime and structural maintenance on the hull of the ship to reduce the hull resistance and the component losses.

2.1.1.7 Effect of ideal Optimization

In Figure 8, the design processes from *"Håndbok for prosjektering av brennstofføkonomisk fartøy"* by *Norges Skipsforskningsinstitutt* is presented. The arrows on the left side shows the transport fuel reduction potential for the given decision suggested by the book.

Modern tools and recent development in engine technology has led to an in general more efficient shipping technology. It is therefore expected that factors like "main dimensions", "power system" and "speed" may have a greater impact than indicated in Figure 8.

Figure 8 Decision Logic and Potential Cost Reduction. The numbered percentage will be discussed in chapter [68].



2.1.2 Basic Principles of Hull Resistance

There are several parameters affecting the power needed to move the ship through water. Hull resistance in water can be divided into three groups [12]:

- Frictional resistance
- Residual resistance
- Air resistance

In addition to the resistance components of a hull in calm water, there are several coefficients and parameters that are used to indicate a ship´s hull capabilities that are explained further in appendix H. In section 2.1.2 the three groups of hull resistance will be explained.

The towing-resistance of the hull are not necessarily the power-speed curve since several factors such as propulsion losses are excluded in the hull resistance estimations. The power-speed curve can be estimated through simulations. The hull resistance is anyhow important to discuss parameters affecting the power-speed curve.

A hull´s resistance in water is comparable with an arbitrary box moving on a surface. To overcome the friction and move the ship, the force moving the ship has to be greater than the sum of all the friction components.

2.1.2.1 Bernoulli´s law

The dynamic properties of water can be described by using Bernoulli's law for dynamic pressure. This is shown in Formula 1.

Formula 1 Bernoulli's law. ρ and v represents the density and speed of water [12]

$$\frac{1}{2} \cdot \rho \cdot v^2 + \rho \cdot g \cdot z + p = K$$

The dynamic pressure is used to calculate the source-resistance of water on a hull. If water is moved or stopped by force, the dynamic force will have a resulting force on the hull. The dynamic properties of water are used when calculating C, which is the dimensionless resistance constant related to the source resistances R through the reference force K (Formula 3). This force, K, is defined as "the force which the dynamic pressure of water with the ship's speed v exerts on a surface which is equal to the hull's wetted area $A_{s.}$" [12]. K can be explained as in Formula 2. K are used to estimate frictional-, residual- and air-resistance.

Formula 2 Reference Force K. As is the wetted area and is multiplied with Bernoulli's law. [12]

$$K = \frac{1}{2} \cdot \rho \cdot v^2 \cdot A_s$$

The source resistance is found by the reference force times a source specific constant C. This is shown in Formula 3.

Formula 3 Source resistances R found through the dimensionless resistance constant C and the reference force K. [12]

$$R = C \cdot K$$

C can be found through several theoretical estimations such as *Holtrop 84 and Mennen* [13], but in general practice [9] the best ways of estimating a precise C is through model test tanks and CFD estimations.

2.1.2.2 Frictional resistance

The friction of the hull is based on friction between the water and the hulls wetted surface. Because of this, the frictional resistance R_F increases when the wetted surface A_s increase. The friction also increases by fouling of the hull. This is a very common problem in maritime applications and paint developers have through decades been working on finding the paint with the best anti-fouling characteristics and the lowest impact on the environment. Regulations has been made to avoid use of for example TBT (tributyltin) [12], since it has a big harm on surrounding environment.

The ship´s frictional resistance in general increase when the speed increase at a rate that is equal to the square of the vessel's speed [12]. This is also shown in Formula 2. The viscous resistance is also dependent on the Reynolds-number. This meaning that when the waterflow along the hull changes the Reynolds-number also changes. If the ship leaves one flow regime and enters another the power can in some cases also decrease because of turbulence [11].

The ship´s frictional resistance in water is a major part of the overall hull resistance. For low-speed ships as much as 70-90% [12] of the resistance can be as a result of friction. For high speed vessels like cruise liners and containerships, sometimes less than 40% [12] of the resistance is a result of friction. Formula 4 shows the relation between C_F, R_F and K.

Formula 4 Frictional Resistance of a ship. R_F is the frictional resistance, C_f the frictional coefficient and K_F the dynamic pressure force. [12]

$$R_F = C_F \cdot K_F$$

2.1.2.3 Residual resistance

Residual resistance consists of the losses caused by generating waves and eddies around the ship. In general, the residual resistance of ship represents 8-25% [12] of the total resistance for low-speed ships and 40-60% [12] for high speed ships. These numbers may vary.

For waters with water depths less than ten times the draught of the ship, shallow water characteristics makes the resistance higher. This is because of the water passing underneath the ship hull meets resistance [12].

Wave resistance for low speed vessel can be said to be proportional to the square of the speed, but this is not valid for higher speed according to empirical data [12]. If the vessel enters higher speed, the resistance increases more rapidly. This explains why residual resistance represents a higher share of the total resistance for high speed vessels. The residual resistance can be described as in Formula 5.

“The residual resistance is “invented” more like a result of techniques used to document ship resistance.

From a model test the towing resistance is found. Then known components are calculated and subtracted from the towing resistance. The rest is then called *residuary”* [9].

Formula 5 Residual resistance. R_R is the residual resistance, C_R the residual resistance coefficient and K the dynamic pressure force. [12]

$$R_R = C_R \cdot K_R$$

2.1.2.4 Air resistance

Air resistance for a ship is a minor contributor to the overall resistance. As little as 2% [12] of the total resistance is air resistance for many ships, while it is as high as 10% for some container carriers. R_A can in calm water in principle be proportional to the square of the ship’s speed.

The relation between R_A, K_A and C_A can be described as in Formula 6.

Formula 6 Air resistance for ships. R_A is the air resistance, C_A the air resistance coefficient and K_A the dynamic pressure force. [12]

$$R_A = C_A \cdot K_A$$

MAN Diesel and Turbo [12] uses a formula to calculate the air resistance for a ship in calm waters as given in Formula 7. The formula is based on the assumption that 90% of the dynamic pressure of air with a speed of V, i.e.:

Formula 7 Air resistance for a ship, calculated. R_A is the air resistance, ρ the air density, v the speed of the ship through the air and A_{air} the area that hits the air. [12]

$$R_A = 0.9 \cdot \frac{1}{2} \cdot \rho \cdot v^2 \cdot A_{air}$$

Were ρ is the density of air and A_{air} is the area of the hull that is over the waterline.

2.1.3 Calm water hull resistance

Based on the simple hull resistance theory presented in section 2.1.2 the towing resistance of the hull can be described as in Formula 8.

Formula 8 Towing resistance of a hull summarized by frictional-, residual and air-resistance. [12]

$$R_T = R_F + R_R + R_A$$

The model tests indicate the calm water prognosis for the hull resistance. Typical towing test are illustrated in Figure 9. The ship is moved through calm water and the power used is measured. This prognosis does not represent the power-speed curve. The power-speed curve is the power delivered to the propeller which means that propeller-losses and other losses that is not included in the towing tank test has to be included to find the power-speed curve. This can be done through several simulation methods.

Figure 9 Towing test in MARINTEK´s testing facility in Trondheim. [9]

The necessary towing power can be described as P_E as shown in Formula 9.

Formula 9 P_E – Towing power

$$P_E = R_T \cdot V$$

In general, the resistance of high speed and low speed ships can be illustrated as in Figure 10. The main difference between high speed and low speed vessels is the wave friction.

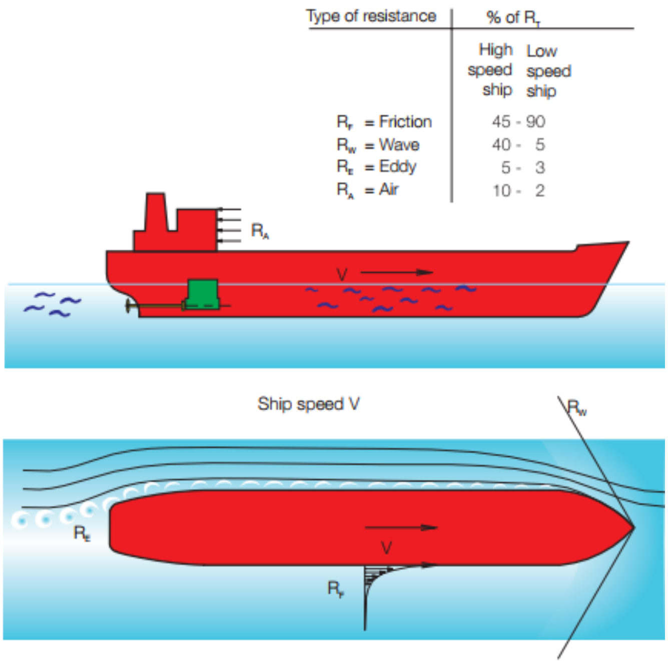


Figure 10 High Speed and Low speed vessel resistance. [12]

The resistance of a ship increases exponentially with speed. This is because of the increase in the different resistance components of the hull. This means that a hull that is designed for a 15 knots service-speed may have to double the power needed only to increase the speed by a few knots. This is illustrated in Figure 11 [12].

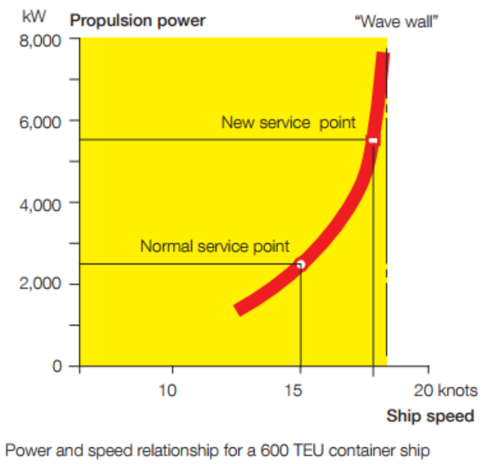


Figure 11 Power-speed curve for a typical container ship. [12]

The resistance of a hull is increasing through its lifetime. This is because of buckled plates and fouling. The resistance can increase with as much as 25-50% [12] through its lifetime.

Unfortunately, no sources have been found on increased resistance as a function of type or size of the ship. To check the impact on the speed-power curve due to increased size, the parameters have to be run through a CFD software and new adjustments have to be made. For bigger ships the increased resistance due to bad weather is anyhow less than for smaller ships.

2.1.4 Propulsion

The towing resistance represents the necessary kW for towing the ship with a given speed. The power-speed curve is the necessary power delivered to the propeller to obtain I given speed. To find the power speed-curve by use of the towing resistance, the propulsion losses has to be estimated.

The choice of propeller is an optimization problem with several factors affecting the end result. It is also important that the engine and the propeller are designed to work together [11]. The difference between the towing power and the propulsion power can in some cases be up to 40% [9].

The different calculations made to select the suitable propeller are not further discussed in this master´s thesis.

2.1.5 Admiralty Coefficient, A

The admiralty coefficient can be used to estimate the relation between speed, draft and power for the ship as in Formula 10 [12]. For the *Admiralty Coefficient,* V is the speed of the ship studied, V_{des} is the design speed of the ship, P the studied power and P_{des} the design power. ∇ is the displacement studied and ∇_{des} is the design displacement.

Formula 10 Admiralty Coefficient, A. [12]

$$\mathrm{A} = \frac{\nabla^{\frac{2}{3}} \cdot \mathrm{V}^3}{P} = \frac{\nabla^{\frac{2}{3}}{}_{des} \cdot \mathrm{V}^3{}_{des}}{P_{des}}$$

For instance, this can be used under conditions with equal propulsion power as in Formula 11 [12].

Formula 11 Admiralty coefficient for equal propulsion power. [12]

$$V = V_{des} \cdot \left(\frac{\nabla_{des}}{\nabla}\right)^{\frac{2}{9}}$$

Or for equal ship speed if for example the goal is to find the effect of increasing the cargo load with 10%, as in Formula 12 [12].

Formula 12 Admiralty coefficient for equal speed. [12]

$$P = P_{des} \cdot \left(\frac{\nabla}{\nabla_{des}}\right)^{\frac{2}{3}}$$

If design speed, design power or design displacement is known, this can be used to estimate necessary power, displacement and speed for other values as well.

An example of an admiralty function is shown in Figure 12 based on a reference vessel with design speed 15 knots and design speed power 1000 kW.

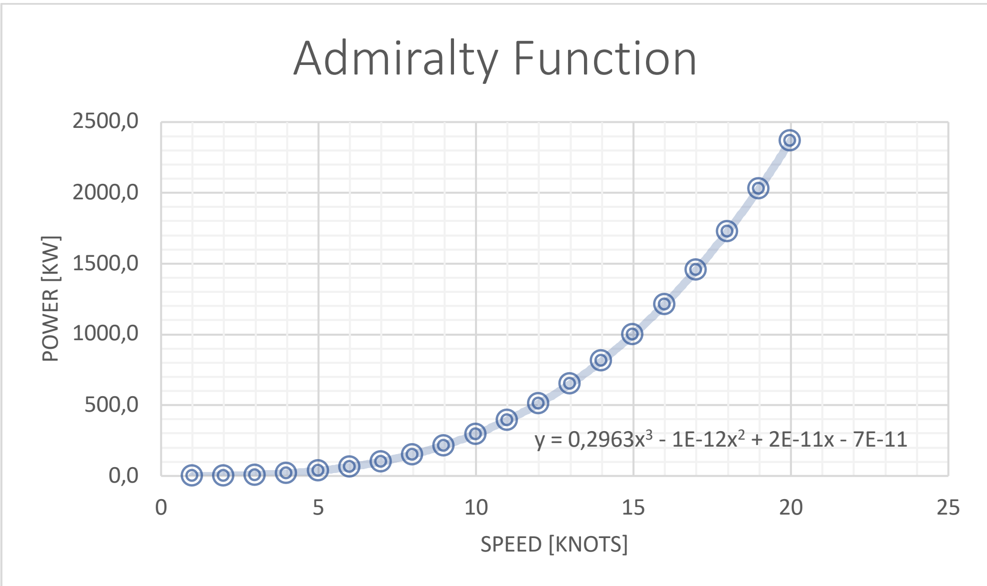


Figure 12 Admiralty Function for a ship with design speed 15 knots and design power 1000 kW.

2.1.6 Auto-generation of power-speed curves

Models for ship-resistance can be obtained by for example using the method specified by *Holtrop 84 and Mennen* [14]. To calculate a ship resistance, a broad range of factors have to be considered. To identify and determine all these variables, the ship design logic specified in section 2.1.1 has to be followed and design demands from end user has to be satisfied. Therefore, it is not necessarily the most energy efficient hull that is used in the end. As shown in Figure 13, there is a trade-off between displacement (deadweight), capabilities and weather. In addition, factors such as bottom conditions, noise, possible operation areas and customers may affect the final design.

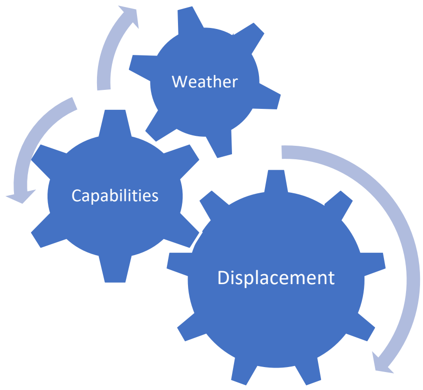


Figure 13 Trade-off for efficient hull optimization.

2.1.7 Sea Margin

For ships in operation, calm water rarely happens. However, the calm water resistance is up to moderate seas often the dominant contributor. Hence it is important to have a good estimate of these forces. To estimate moderate seas and above, additional forces have to be added. To collect all variations of weather the ship is operating in through one year so that the additional resistance can be averaged and used to estimate the energy consumption of the same period, ship designers define an added resistance called *sea margin*.

During extreme weather, the wind gusts and extreme waves are the variables to determine the capabilities of the ship [12]. The capability study shows under which condition the ship is capable of holding position with the given hydrodynamic capabilities and the available power. To increase the capability, the hydrodynamic performance either have to rectify or the available power has to be increased.

According to Magnussen [15], the most common sea margin added to design analysis today is 15%. In her research done together with the *Norwegian University of Science and Technology* and *Smart Maritime* results shows that 15% is lower than the expected sea margin for ships operating in the Atlantic- and Pacific Ocean. Together with Smart Maritime, Magnussen shows that for a trans-Atlantic sea route a sea margin of 18.6% may be added.

To dimension the max power necessary to achieve the requested capabilities, a capability study may be done. In Havyard Design and Solutions AS, capability studies are done to optimize the engine configuration. If the capability of the ship is too low, an option can for example be to increase the available power.

Smart Maritime are currently developing a tool called *GYMIR* for estimating the added energy consumption through one year for ships. By using the hull in the design studied and the attached power-speed curves and simulating a one-year cycle, the actual energy consumption can be found. *GYMIR* uses weather data collected by weather stations and data simulated by wave-, wind and current models to generate a weather profile for the route sailed.

Modelling sea margin for a vessel is a challenging operation. The resolution of the data is extremely important. Wave theory shows the complexity of ocean waves and lightens the need for data with a high resolution to show the peaks in ship resistance.

2.2 Route Studies

Route studies are used to simulate the environment that a ship is operating in. To estimate the average energy consumption and the power curve through an operation, a route study is crucial. There are few or no representative theoretical work regarding route studies representative for this master´s thesis, therefore, this theory section will cover weather factors, modelling theory and power factors for ships.

Additional theory that can be useful for understanding weather modelling for ships can be found in appendix I-K. Wave-, wind- and current theory that can be useful for deciding sea margin and capabilities can be found there.

2.2.1 Weather factors

Waves, current and wind are all factors increasing the power consumption for a ship. Wind and currents are increasing the power needed from the propellers to obtain the ship´s speed in waters. Waves are leading to motions in different directions for the ship that it will have to compensate for, in addition to slamming and other phenomena reducing the ships speed.

For ship motions, the vertical motions have the most significant impact on the power consumption of the ship. Calculating added resistance due to waves in any other direction than head seas is very complicated and is less important for the power consumption. Head sea conditions is the most severe and will represent the maximum added resistance [16].

Added resistance due to wind can be important for ships like passenger vessels and ferries due to the large superstructure of the ship. By using aerodynamic designs, the resistance can be decreased [16].

Wave-, wind- and current-theory are discussed further in appendix I, J and K.

2.2.2 Modelling weather

Simulating a ship in different weather conditions demands advanced computer power and knowledge in oceanography, atmosphere, hydrodynamics and engineering. Generating a tool to find the optimal trade-off between capabilities, hydrodynamic performance, cost and design is advanced.

The most common way of estimating the power needed to power a ship by modern standards, are by using sea margins. Average weather conditions can be used to estimate the energy needed to move from A to B, while extreme weather conditions (for example wind gusts) are important to for example ensure sufficient power needed to more the ship in harsh conditions.

The Norwegian Maritime Authority is the legislative organization for ships operating in Norwegian waters. They have decided that ships should be designed to operate in the sea margin that they are intended to. Therefore, four different operational areas *(Norwegian: fartsområde)* with different limitations and weather conditions has been agreed upon.

2.2.3 Route Studies at Havyard Design and Solutions AS

In lack of other sources explaining sea margin modelling, Havyard Design and Solution AS [9] has been used as a reference for sea margin modelling.

First, the calm water performance of the ship is found. This assumes a clean hull and an ideal weather condition.

Weather data are gathered from the operational areas of the ship. By doing this a weather window for a given period (a day, a year or ten years) are given. This is used to say something about how many hours a year the ship operates in the different weather conditions.

The impact of weather on the power-speed curve is modelled. This is used to estimate how much power that are necessary to keep the ship at a given speed in different weathers. Having this and the weather window for the operational area, a sea margin can be estimated.

By studying the weather expected for the operational area the capability of the ship can also be discussed. There is also a trade-off between safety, operational needs, customer needs and more to evaluate what weather the ship should operate in.

2.3 Engine setup/Energy Supply

The powertrain of a given system varies in efficiency when load changes. An effective estimation of the functioning powertrain and power integral characteristics for a certain time period needs to take into account all varieties of power operation conditions. Factors that affect the efficiency of the energy consumption are e.g. reactive power variation, voltage in power-system, power consumption, power generation, etc. [17]

Energy losses need to be defined with a high accuracy and reliability to be able to say something about the energy demand for ships. Energy losses are also very important to determine how to design a reliable powertrain.

Variation in loads has great impact on the thermodynamic and mechanical efficiency of an engine. To achieve a steady state combustion, it is beneficial to keep the load constant. One of the reasons for this is that as load varies, internal temperature in affected components also changes. Different temperatures may increase the friction or transition resistance, which again decreases the efficiencies [18].

Most common engines are tuned and tested by the manufacturer. These reports are valuable information when designing a ship powertrain and need to be taken into consideration. By combining the suitable engines an optimal energy efficiency can be achieved.

The following sub-sections provides an introduction to combustion theory and engines as well as batteries and fuel cell solutions used for comparisons in section 3 and 4.

2.3.1 The Carnot Heat Engine

One of the first principles stating the theoretical thermal efficiency of a heat engine was presented by Nicolas Leonard Sadi Carnot in 1824 and later named *The Carnot Heat Engine* [18].

A heat engine is a cyclic device were a working fluid changes from one state to another releasing heat. The work is done by the fluid on a system in one part of the system, and from the system on the fluid on another part. The net change in potential energy in these two fluids represent the net work.

In Figure 14, the *Carnot Heat Engine* (hereby CHE) is presented graphically illustrating the four different processes in a volume-pressure schematic. To achieve an optimal net work, thus the cycle efficiency, one way is to use the system that requires the least amount of work and deliver the most, hence the reversible processes. This theoretical process cannot be achieved because of the irreversibility's of such a process [18].

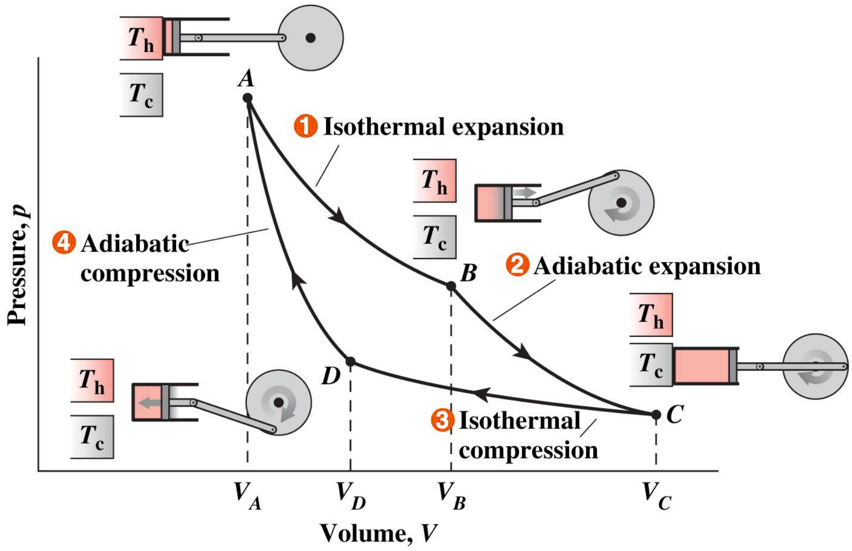
The *Carnot Heat Cycle (hereby CHC)* consists of four reversible processes (hence theoretical processes), all shown in Figure 14. Two of the processes are isothermal which means that there is no change in temperature, described as in Formula 13.

$$T_H = Constant$$

Formula 13 Isothermal Process Principle

The two other processes are adiabatic, hence there is no heat distribution between the heat engine and the surroundings.

Figure 14 The Carnot Heat Engine [18].



A CHE is running by two heat reservoirs, T_H and T_c. The potential between the two reservoirs is the potential net work. According to Yunus A. Cengel et. Al;

"Since the energy reservoirs are characterized by their temperatures, the thermal efficiency of reversible heat engines is a function of the reservoir temperatures only. That is,

$$\eta_{th,rev} = g(T_H, T_L)$$

or

$$\frac{Q_H}{Q_L} = f(T_H, T_L)$$

since

$$\eta_{th} = 1 - Q_L/Q_H. \quad "$$

Even though the main principle of the *CHE* does not represent the compression-ignition (Hereby CI engines) engines for diesel or LNG powertrains, it represents important theoretical elements for traditional combustion engines as well. The efficiency of a CHE can be presented as in Formula 14 and Formula 15.

$$\eta_{th} = 1 - \frac{Q_L}{Q_H}$$

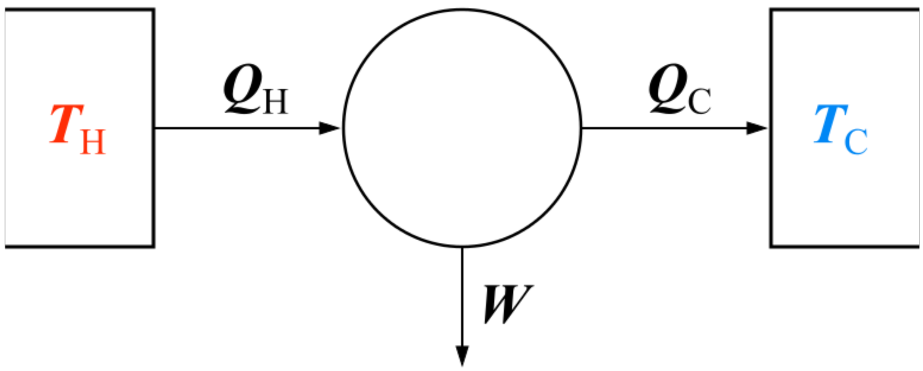
Formula 14 Efficiency for a CHE.

$$\eta_{th} = 1 - \frac{T_L}{T_H}$$

Formula 15 Efficiency for a CHE is found by the relation between the low temperature zone (after utilization) and high temperature zone (before utilization). Heat is energy and the efficiency relate the heat utilized.

In modern applications, the relation between the two heat reservoirs and the net work are often illustrated as in Figure 15 [18]. Since there is no heat loss in the process, Formula 14 express the efficiency of the Carnot cycle. In general, no engine operating between two heat reservoirs can be more effective than the CH-engine, simply because there is no loss in this process.

Figure 15 The Carnot Heat Engine illustrated in a modern way [18].



To use the CHE-principles in a combustion engine, the operating temperatures has to be considered. By using the theoretical CHE process and the representative compression ratios for the different engines, the thermal efficiency relation can be found.

2.3.2 The Otto Cycle

The ideal cycle for spark-ignition (Hereby SI) reciprocating engines are called the *Otto Cycle* (Hereby OC), named after the German scientist Nikolaus A. Otto who successfully built a four-stroke engine in Germany in 1876. The OC is executed in a closed system, so given the stages described in Figure 16, the theoretical energy conversion in the process can be described as in Formula 16 [18].

$$(q_{in} - q_{out}) + (w_{in} - w_{out}) = \Delta u$$

Formula 16

By looking at the two heat transferring processes in Figure 16 (2-3 and 4-1), it can be explained that no work is done. This is further shown in Formula 17 and Formula 18 [18].

$$q_{in} = u_3 - u_2 = c_v(T_3 - T_2)$$

Formula 17 Process 2-3 is a constant-volume process where heat is transferred to the working gas from an external source.

$$q_{in} = u_3 - u_2 = c_v(T_4 - T_1)$$

Formula 18 The system is completed by another constant-volume process where heat is rejected.

The air-standard assumptions are important in the following formulas to come. They are used to state thermal efficiency equations for the Otto-Engine, the Diesel-Engine and the Brayton Cycle (the gas-turbines) [18].

- The working fluid is air, which continuously circulates in a closed loop and always behaves as an ideal gas.
- All the processes that make up the cycle are internally reversible.
- The Combustion process is replaced by a heat-addition process from an external source.
- The exhaust process is replaced by a heat-rejection process that restores the working fluid to its initial state.

In addition, the *cold-air-standard assumptions* (Hereby cold-air assumptions) states that the air has constant specific heat for air in room-temperature (T=25°C) [18].

Using the cold-air assumptions, the thermal efficiency for an Otto-Engine, $\eta_{th,Otto}$, can be described as in Formula 19 [18].

$$\eta_{th,Otto} = \frac{W_{net}}{q_{in}} = 1 - \frac{q_{out}}{q_{in}} = 1 - \frac{T_4 - T_1}{T_3 - T_2} = 1 - \frac{T_1(\frac{T_4}{T_1} - 1)}{T_2(\frac{T_3}{T_2} - 1)}$$

Formula 19 Thermal Efficiency for the Otto-Engine 1. If the same heat is rejected from the process in 4-1 as added in 2-3, $\eta_{th,Otto} = 1$.

By looking at Figure 16, whom can see that processes 1-2 and 3-4 are isentropic and that 2-3 and 4-1 are constant volume processes.

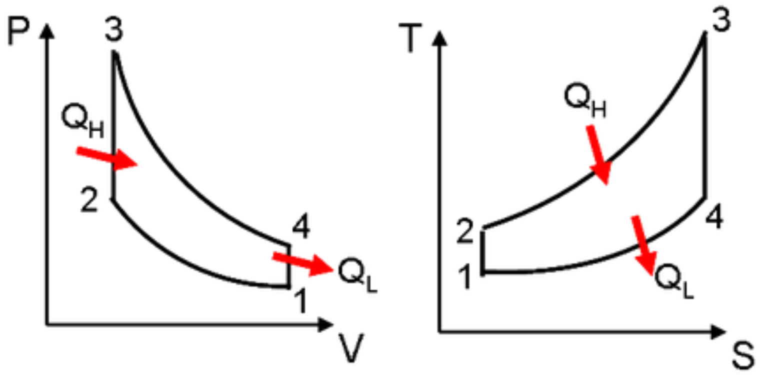


Figure 16 T-s- and P-V-diagrams for the Otto Cycle [18].

Because of the isentropic property of process 1-2 and 3-4 and the constant volume property of 2-3 and 4-1, we can write that

$$\frac{T_1}{T_2} = \left(\frac{V_2}{V_1}\right)^{k-1} = \left(\frac{V_3}{V_4}\right)^{k-1} = \frac{T_4}{T_3}$$

Formula 20 [18]

Using Formula 20, the second thermal efficiency formula can be written as in Formula 21 [18].

$$\eta_{th,Otto} = 1 - \frac{1}{r^{k-1}}$$

Formula 21 Thermal Efficiency for the Otto Engine 2.

In Formula 21, r is the compression ratio and k is the specific heat ratio c_p/c_v. The thermal efficiency increases with both the compression ratio and the specific heat ratio. Friction and necessary chemical bounding to avoid auto-ignition and engine knock are the main reasons for increased resistance in the engine and hence less thermal efficiency than in the ideal Otto Cycle [18].

An increased engine efficiency can be achieved by introducing monatomic gasses as argon or helium, to increase the specific heat. When using air, as most cars are doing, the combustion process have to feed through bigger molecules as CO_2 [18].

The thermal efficiencies of modern spark-ignition piston engines vary from around 25% to 30% [18]. Otto engines are rarely used for maritime applications. One of the reasons for this is that diesel engines (principle described in section 2.3.3) operate at a higher temperature and therefore has a higher compression ratio. This makes the diesel engine more efficient than the Otto-engine.

2.3.3 Diesel Engines

The diesel cycle is one of the *compression ignitions* (hereby CI) reciprocating engines. In 1890s, Rudolph Diesel presented his suggestions for a diesel combustion system similar with what we today recognize as the *Diesel Engine.* The CI reciprocating diesel engine is very similar to the spark ignition engine (gasoline engine) in function, while the two main differences is the fuel and the compression-ignition versus the spark-ignition.

Diesel engines are in most cases more efficient than gasoline engines. This is because of the auto-ignition issues in gasoline engines. To avoid the issue of having an auto auto-ignition and engine knocking in gasoline engines, stringent requirements introduce chemicals needed in the refinery processes. The elimination of auto-ignition processes in CI reciprocating diesel engines opens up the possibility of operating the engines at a much higher compression ratio, typically between 12 and 24 [18].

The process that Rudolph Diesel presented in his research is shown in Figure 17. The air pressure inside the piston is increased until a given pressure state is set, then fuel is injected, and the ignition happens. The ignition continues in the first part of the process (2-3) and is therefore a constant pressure heat addition processes. The isentropic processes in 1-2 and 3-4 does not differ from the gasoline piston engine process [18].

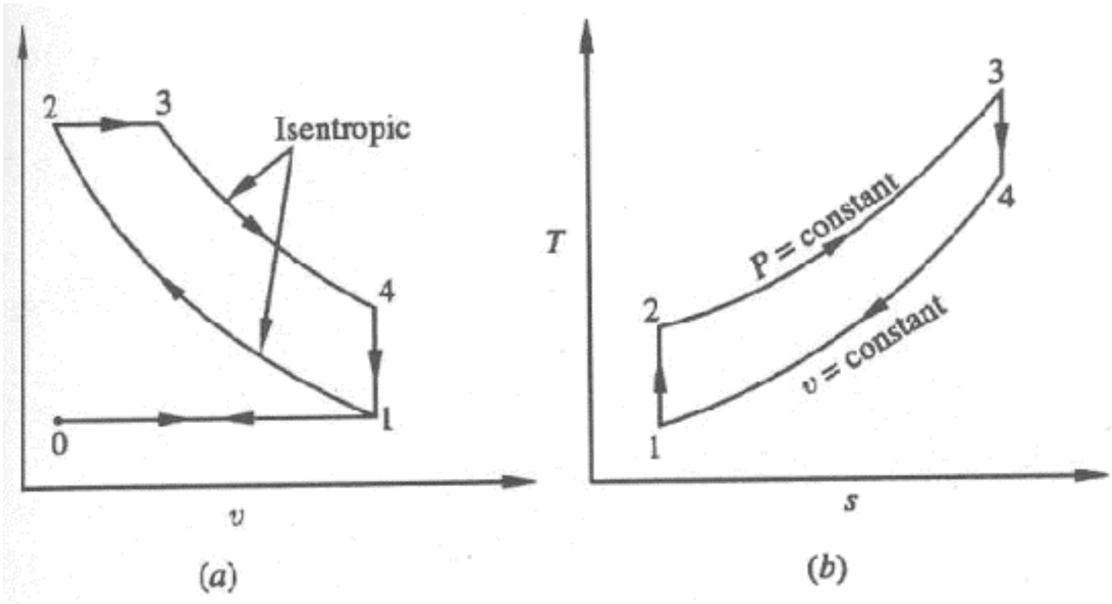


Figure 17 P-V- and T-s diagrams for Diesel engines.

The heat injection at a constant pressure 2-3 (q_{in}) and the heat rejected in the constant volume in 4-1 ($-q_{out}$) do theoretically happen in a closed process. Therefore, the heat injection process can be explained as shown in Formula 22, Formula 23 and Formula 24 [18].

$$q_{in} - w_{b,out} = u_3 - u_2$$

Formula 22

$$q_{in} = P_2(V_3 - V_2) + (u_3 - u_2) = h_3 - h_2 = c_p(T_3 - T_2)$$

Formula 23

and

$$-q_{out} = u_1 - u_4 \longrightarrow q_{out} = u_4 - u_1 = c_v(T_4 - T_1)$$

Formula 24

Given the cold-air assumptions, the ideal Diesel cycle becomes as shown in Formula 25 [18].

$$\eta_{th,diesel} = \frac{W_{net}}{q_{in}} = 1 - \frac{q_{out}}{q_{in}} = 1 - \frac{T_4 - T_1}{k(T_3 - T_2)} = 1 - \frac{T_1(\frac{T_4}{T_1} - 1)}{kT_2(\frac{T_3}{T_2} - 1)}$$

Formula 25 Thermal Efficiency in the ideal Diesel Cycle.

The cut-off ratio r_c can also be used to calculate the thermal efficiency of the diesel process. The cut-off ratio (Formula 26) represents the ratio between the cylinder volumes before and after the combustion processes, hence the ratio between the volume in 2 and 3 in Figure 17 [18].

$$r_c = \frac{V_3}{V_2}$$

Formula 26 The cut-off ratio from Figure 17.

When having the cut-off ratio, it can combined with the isentropic ideal-gas relations for process 1-2 and write Formula 27 [18].

$$\eta_{th,Diesel} = 1 - \frac{1}{r^{k-1}}\left[\frac{r_c^k - 1}{k(r_c - 1)}\right]$$

Formula 27 The thermal Efficiency relations based on cut-off ratios [18].

The compression, r, is a key factor in this. If we assume cold air conditions, the thermal efficiency of the gasoline-engine is *higher* than for the diesel engine. But since compression ratio, *r*, for the diesel engine is typically between 12-22 while it for the gasoline engine is typically 8-10, the diesel engine is in practice more efficient [18].

Another reason for why the diesel engine is more efficient, is that it operates at a lower rpm than the gasoline engine and that the air-fuel ratio is much higher for CI engines than for SI engines. According to Y. A. Cengel et. Al, thermal efficiencies for gasoline engines varies from 25% to 30%, while it for modern large diesel engines varies from 35% to 40% [18]. For super-large engines used at e.g. container ships the efficiency can be even better.

2.3.3.1 Powertrain build-up and Efficiency

Studying different factors affecting efficiencies for a diesel-engine ship may be a complex operation. This section will present some of the important factors affecting the efficiency of a diesel engine, to give a broader understanding of the efficiency limits and the challenges.

Xavier Tauzia et. Al. [19] published in 2013 a paper where a study of automotive Diesel engine efficiency when running on stoichiometric conditions was documented. The study describes many of the efficiency variables as well as emissions variables (will be presented in section 2.3.3.4.).

To better understand how diesel engines in ships are running, two powertrains designed by Rolls-Royce Marine will be presented [20]. The diesel electric system is shown in Figure 18 and a hybrid diesel mechanic propulsion system in Figure 19.

Figure 18 illustrates how a pure diesel electric propulsion system are designed. The Diesel Engine generates electricity through a generator and feed the electricity through the switchboard. The electric drives running the propulsion are connected to the switchboard. To evaluate the brake power efficiency (BPE), the losses in the generator, the cabling, switchboard, converters, etc. will have to be considered.

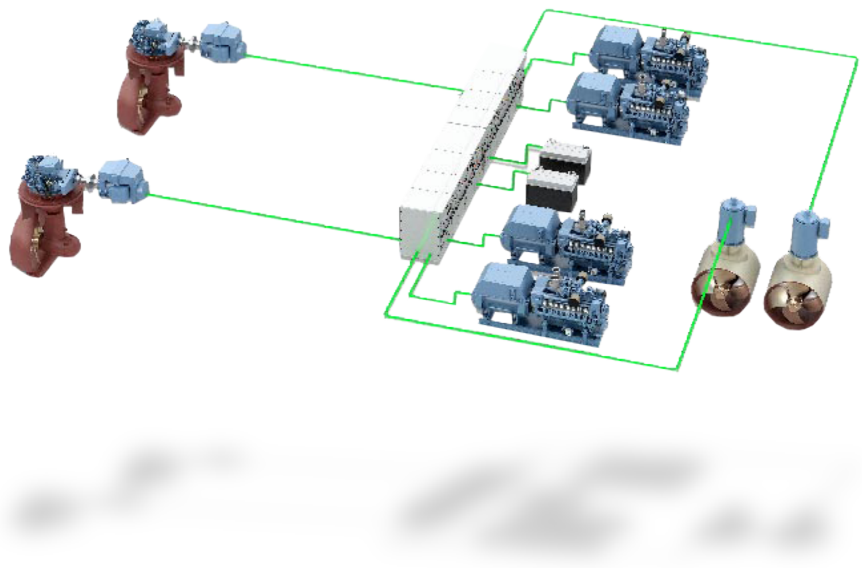


Figure 18 Diesel Electric Propulsion System [20].

Figure 19 illustrates a hybrid shaft generator system. The main difference between the diesel electric propulsion system and the hybrid shaft generator system is that the hybrid shaft system opens up the possibility of not converting the energy from mechanical energy to electric energy from the engine to the shaft. Even though there are losses in the gearbox connecting the engine and the shaft, the mechanical losses in the hybrid shaft generator system may be less than for the diesel-electric propulsion system.

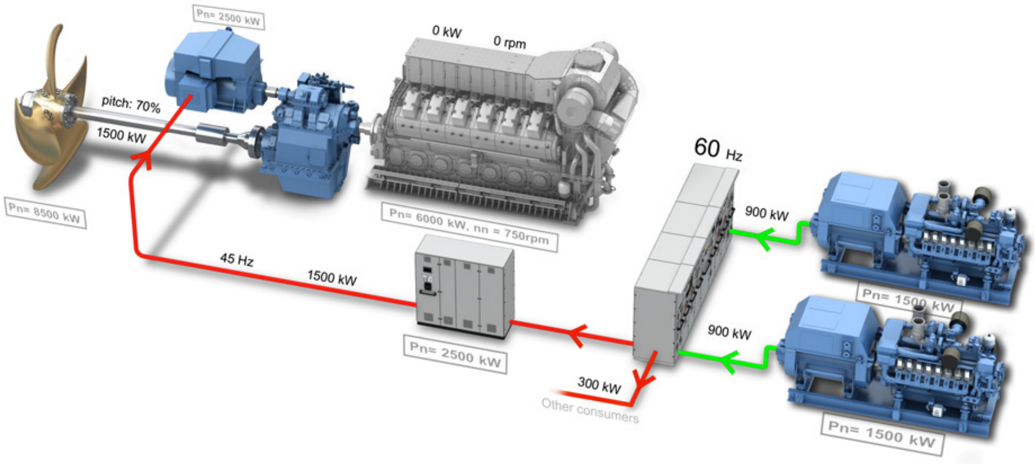
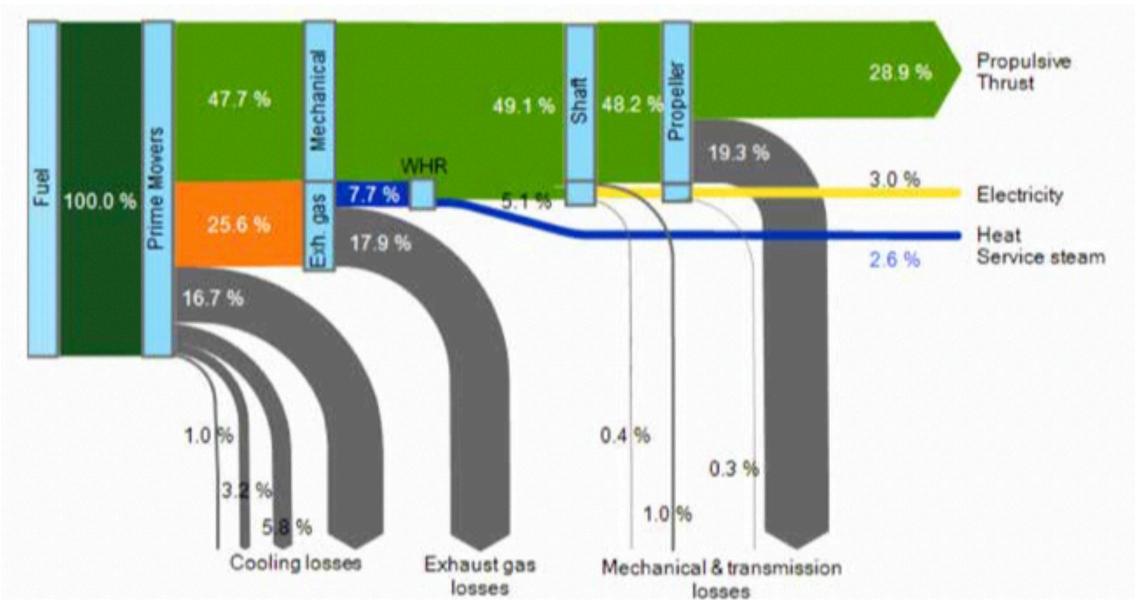


Figure 19 Hybrid Shaft Generator System [20].

In general, the most dominant losses in most fossil fuel systems are represented by the losses in the combustion engine itself. This is illustrated in Figure 20 [21]. In this master thesis, it is assumed that all ships are moved by propellers. It is assumed that the propeller losses are the same for any of the systems. Converters, switchboards and cabling are also not significantly different for propellers with electric drives. To make a tool able to compare the emissions and efficiencies for the different systems mention in this project, the combustion engine or the battery itself is therefore in focus.

Figure 20 Energy flow in a powertrain [21]

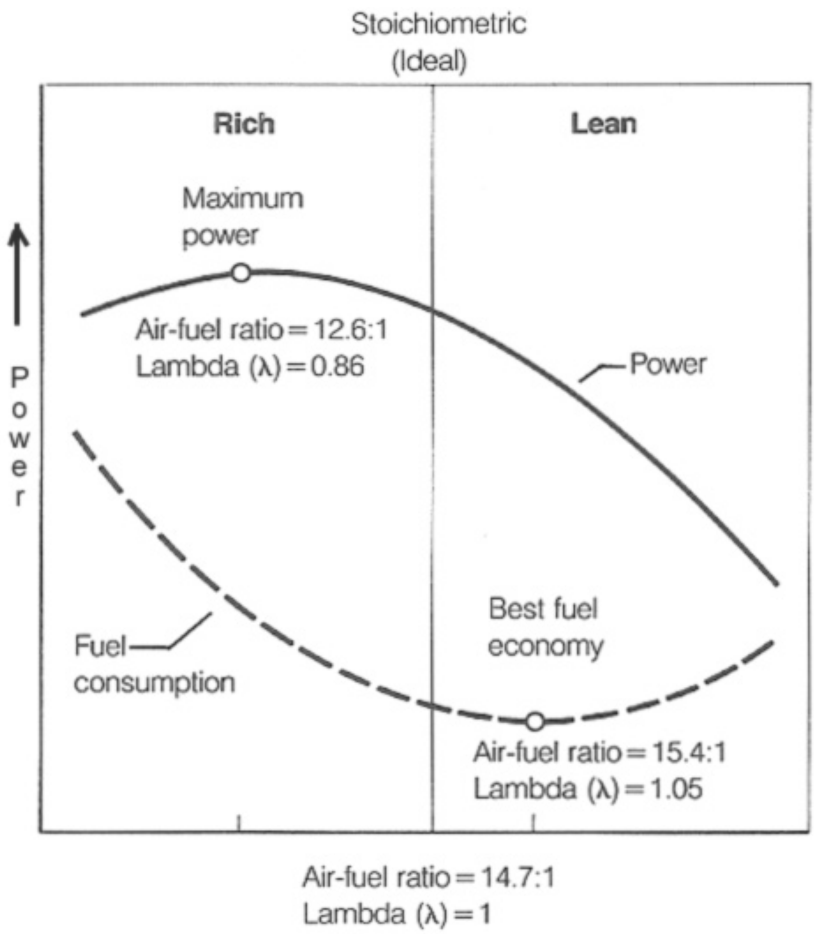


The main indicated thermal efficiency affecting factor is the air-fuel ratio (AFR). To achieve a stoichiometric combustion, which means that there is no fuel or oxygen left in the cylinder after the combustion is completed, the AFR for most diesel-fuels are 14.7/1 [19]. The stoichiometric combustion-relation is not necessarily the most efficient combustions since the stoichiometric combustion demand ideal gas assumptions. According to Xavier Tauzia et. Al., increased power can be achieved by rich combustion and more efficient combustion can be achieved by lean combustion, this is shown in Figure 21. This figure is an important indicator for understanding efficient thermodynamic combustion. Increasing the engine loads leads to variations in the thermal efficiency, hence losses.

Mechanical losses are also a major contributor to losses in combustion engines. Some of the rotating elements experience increased resistance at higher rpm, while other experience the opposite.

There are several patents for increasing the efficiency of the engine. Lambda sensor and EGR-valves are both examples of inventions optimizing the air-fuel ratio. The technical details and how these components work is not a field of study in this master´s thesis.

Figure 21 Rich and Lean combustion affecting efficiency and power [19].



The most efficient conventional diesel engines for ships today may achieve an efficiency up to 52% [22]. This may be used in modern long-liners trans-Atlantic container-ships and similar ship designs and are in most cases not suitable for the ship types studied in this master´s thesis.

2.3.3.2 Load Dependent Losses

There are several differences in designing optimal diesel engines. Different engines serve different purposes. In general, it is the air-fuel relation described in the previous section that is critical for the power and the fuel consumption.

Powertrains can be designed to fit the purpose. For double-ended car ferries, the ship in most cases may operate at a low load compared to the maximum load needed in bad weather for maximum capability. In this case, it is effective to design the engine to operate at maximum BSFC (brake specific fuel consumption) at low loads. This means that the air fuel ratio will be at its most efficient (most likely lean) at lower loads. For a trawler operating at higher loads most of the time, the most effective fuel consumption may be at higher loads. Efficiency curves as a function of load or rpm is necessary to say something about the overall fuel consumption of an engine [18].

An opportunity to achieve higher efficiency at different loads is by combining more than one engine. This can be explained by using the engine setup in Figure 18. Each of the engines has a BSFC-load curve, and they can be combined to achieve optimal BSFC. If one of the engines can supply the power-demand alone at peak BSFC, it is ideal to run only this engine. If a higher BSFC is needed, it can be cost-effective to start up several engines to supply the demand. There is an undefined number of configurations that can be assembled for each design and this has to be specified to be able to state the exact combustion. Anyhow, the BSFC is never higher than the CHE-limit and the thermal efficiency limit for the diesel engine [20].

When load changes, the internal temperature of the process also changes. This affects the engine in a way that the process is no longer stable, and to regain stability takes time. In this period (variable in time) the efficiency may be lower than during stable combustion. In general, a constant load and constant rpm is beneficial for the fuel economy. The impact of these accelerations or reductions in load can be reduced by introducing alternative energy carriers/sources such as batteries for peak shaving.

2.3.3.3 Fuel

A reason why it is difficult to produce an exact estimation of emissions and efficiency of a ship or an engine, is that there is a broad range of fuels and fuel specifications that can be used to run the ship. Important characteristics of fuels may be density, viscosity, carbon residue, sediment, compatibility, ash-content and more [23].

The *International Organization for Standardization* published in 1980 the first version of ISO 8217, which sets the maximum and minimum limits of the characteristics described above. The latest version of this standard is ISO 8217:2017 [24]. The most common diesel type for maritime applications in the North-Sea is Marine diesel oil, MGO [24].

The carbon release per burnt unit of fuels is 2.71 kg CO_2/ kg fuel [25]. The lower heating value of the diesel is 11.89 kWh/kg [26].

2.3.3.4 Emissions

The emissions from a diesel engine is related to the efficiency. According to Xavier Tauzia et. Al. [19] there is a trade-off between optimal combustion and efficiency. The stoichiometric combustion is known as the state where there is no oxygen or fuel left in the exhaust.

There are several types of emissions from a diesel engine. The reason why many of these occurs is because of impurities in the air, in the fuel or in the piston.

Carbon Dioxide (CO_2) is the most common exhaust-gas from the combustion and is also a part of the theoretical stoichiometric combustion. The amount CO_2 can be calculated by using the national standardization factors given by *Miljødirektoratet* [25].

Particular matter (PM) is a complex mixture of small particles. PM is toxic and can cause serious health effect for the heart and the lung. Diesel Particle Filters (DPM) are used to remove PM from the exhaust gas in Diesel Engines.

Carbon Monoxide (CO) and *Hydrocarbons* (HC) are emissions from diesel engines that are created as a result unburnt fuel. Varieties in load as throttling and idle increases the amount of CO and HC in the exhaust. CO and HC can cause death. Diesel Oxidation Catalyst (DOC) changes the bounding in the CO and HC and removes the threat.

Nitrogen-Oxides (NO_x) is the name for several types of molecules having Nitrogen and oxygen in it. NO_x is known as one of the most dangerous exhaust gases both for humans, the earth and the atmosphere. It is one of the main gases in the *fog* that is seen over big cities during wintertime and pollutes the ground as well as the oceans. The Selective Catalytic Reduction (SCR), the Lean NOx trap (LNT) and Urea Treatment are three of the methods known for reducing NOx from the exhaust-gases.

Sulphur-Oxides (SO_x) is a molecule presented in the fuel. To reduce SO_x in combustion processes, the SO_x content in the fuel has to be reduced. SO_x can lead to several health problems and governments are working on reducing the SO_x content in the air in cities worldwide.

IMO defines a TIER system valid for ships worldwide. The TIER-system limits the amount of NO_x and SO_x from combustion of fuels operating globally and in emission control areas (ECAs) [7]. PM and CO released from combustion are information given by the manufacturer of the engine. Even though IMO limits two emission factors the engine may pollute less than defined by IMO.

In the stoichiometric combustion, the climate gases above do not occur. As shown in Figure 21, the diesel engine has a less clean exhaust when rich combustion occurs. This is because of the hydrocarbons that are left in the exhaust [19]. Xavier Tauzia et. Al. did three tests of an automotive diesel engine to test efficiency, but they also measured emissions from the engine during their tests. The difference between the tests were mostly injection pressure for the inlet air. As pressure increased, emissions went down.

Cengel et. Al. [18] confirm that there is a trade-off between emissions and efficiency. A common trait for efficiency and emissions is that the diesel engine benefits of running with constant load given that the goal is to optimize the emission and efficiencies.

2.3.4 LNG Engines

In *Thermodynamics – an Engineering approach* by Y. A. Cengel et. Al, the Brayton cycle for gas-turbines has also been described. The Brayton cycle, was first developed around 1870 and proposed by George Brayton for use in reciprocating oil-burning engines. The Brayton cycles main principle is that fuels are used to heat up and increase the pressure of air. When the air is turning back to atmospheric pressure and temperature conditions, it releases energy which is used mechanically in a turbine [18].

An important difference between the combustion process in a gas-turbine compared to a SI- or CI-engine is that the gas-turbine runs with constant flow. The gas is fed into the turbine constantly, not in portions. In the P-V- and T-S-diagrams shown in Figure 22 it is shown that 1-2 and 3-4 are isentropic processes, and 2-3 and 4-1 are Constant-pressure processes [18].

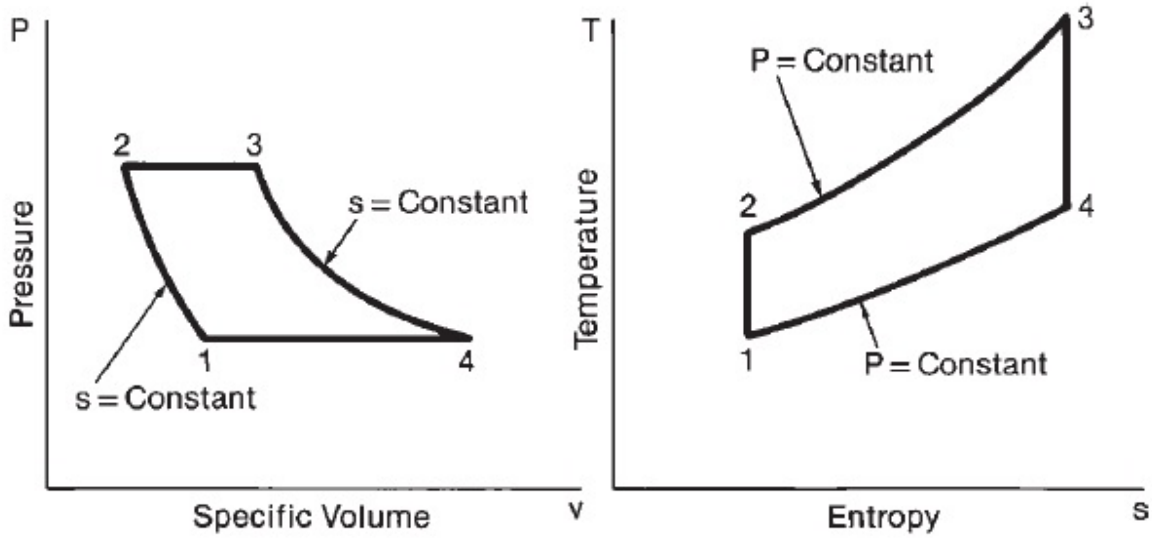


Figure 22 P-S- and T-V-diagrams for the ideal Brayton Cycle [18].

Since the process is a steady-flow process, it can be expressed as in Formula 28 [18].

$$(q_{in} - q_{out}) + (w_{in} - w_{out}) = h_{exit} - h_{inlet}$$

Formula 28 Q is heat, w is work and h is enthalpy.

Since Formula 28 includes all process steps, heat transfer to and from the working fluid are described as in Formula 29 and Formula 30 [18].

$$q_{in} = h_3 - h_2 = c_p(T_3 - T_2)$$

Formula 29

$$q_{out} = h_4 - h_1 = c_p(T_4 - T_1)$$

Formula 30

By using the cold-air-standard assumptions the Brayton cycles thermal efficiency can be stated as in Formula 31 [18].

$$\eta_{th,Brayton} = \frac{W_{net}}{q_{in}} = 1 - \frac{q_{out}}{q_{in}} = 1 - \frac{c_p T_4 - T_1}{c_p(T_3 - T_2)} = 1 - \frac{T_1(\frac{T_4}{T_1} - 1)}{T_2(\frac{T_3}{T_2} - 1)}$$

Formula 31 Thermal Efficiency for the Brayton Cycle 1.

Since both processes 1-2 and 3-4 are isentropic, and the pressure is equal for 2-3 and 4-1 as shown in Formula 32, the thermal efficiency for the Brayton cycle can also be described as in Formula 33 [18].

$$\frac{T_2}{T_1} = \left(\frac{P_2}{P_1}\right)^{(k-1)/k} = \left(\frac{P_3}{P_4}\right)^{(k-1)/k} = \frac{T_3}{T_4}$$

Formula 32 Isentropic processes

$$\eta_{th,Brayton} = 1 - \frac{1}{r_p{}^{(k-1)/k}}$$

Formula 33 Thermal Efficiency for the Brayton Cycle 2.

In Formula 33, r_p represent the pressure ratio between stage 1 and 2, or 3 and 4, or equal as shown in Figure 22.

Gas-turbines operates with a wider range of pressure ratios than the Otto- and the Diesel-engine. The pressure ratio for gas-turbines can vary from 5-20. The wide range of applications for the gas-turbines also makes the efficiency difficult to state, but according to Y. A. Cengel et. Al, “the General Electric LM2500 (Shown in Figure 23) gas turbines used to power ships have a simple-cycle thermal efficiency of 37 percent. The General Electric WR-21 gas turbines equipped with intercooling and regeneration have a thermal efficiency of 43% and produce 21.6 MW” [18].

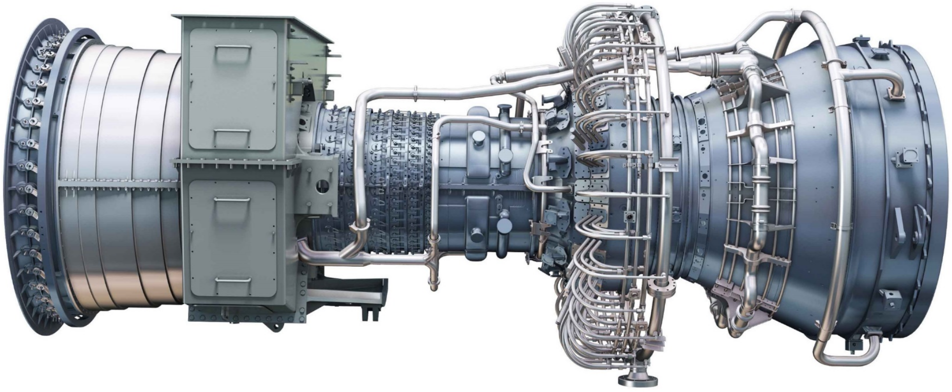


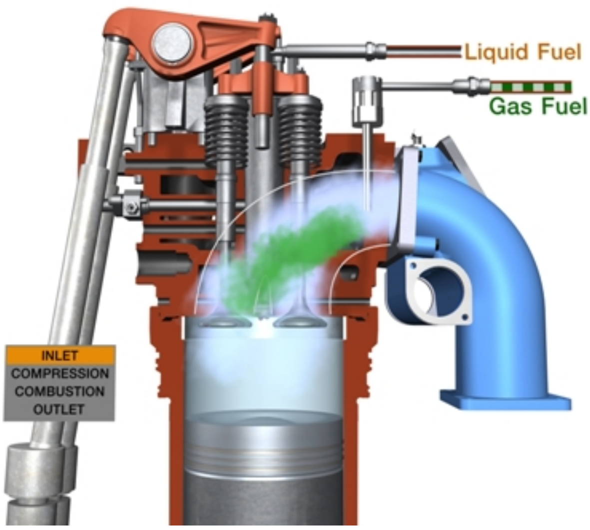
Figure 23 The General Electric LM2500 Gas Turbine [27].

For most maritime applications, gas turbines are not considered due to high cost and lower thermal efficiency. Rolls-Royce (Bergen Diesel) and Wärtsila (among other) have developed dual fuel CI and SI engines running mainly on LNG. Gas turbines are known to be more powerful and because of that, many military vessels use such turbines even though they are expensive and, in some cases, less effective. Where cost efficiency is highlighted, LNG-engines using CI and dual-fuel technology are used.

As seen in Figure 24, dual-fuel CI engines use the same principle as the traditional Diesel engine. Gas Fuel is injected into the piston together with a small amount of liquid fuel. The liquid fuel is necessary to ignite the fuel during compression. Some LNG engines use SI-technology, but to narrow down the project and because SI LNG engines are rare, this report will not describe this technology.

The same pressure-specific Volume and temperature-entropy graphs are valid for the dual-fuel engine in Figure 24.

Figure 24 Wärtsilä Dual-fuel Engine [28].



Wärtsilä is one of the producers of dual-fuel engines. The *Wärtsilä 31DF* (Figure 25) is used as a reference in this project. This is done in agreement with Dirk Folchert, senior sales manager in Wärtsilä.

Figure 25 Wärtsila Dual Fuel Engine [29]

In addition to different engines, LNG also demands different fuel-systems and tank systems. While fuel oil is stored in tanks integrated in the hull, LNG is cooled down and stored in special tanks. LNG also has a natural evaporation rate, which makes it beneficial to have a constant combustion. Leaving LNG stored in a tank for a longer time will result in loss of fuel due to natural evaporation. In a maritime application, the cost of replacing integrated hull diesel tanks with special LNG tanks has to be considered.

CNG (Compressed Natural Gas) is also an option for ship designers. CNG has a lower specific density than LNG and avoids issues with for example natural evaporation. As long as the gas is under pressure and stored safely it is stable. Due to its little use in the Norwegian market, CNG has not been further studied in this master thesis.

2.3.4.1 Powertrain build-up and Efficiencies

The powertrain build-up for ship designed for LNG combustion can be both diesel-mechanic and diesel electric. A description of these two system types and the difference between them are explained further in 2.3.3.1.

The efficiency of a LNG fueled power system can be divided into two separate issues, the gas-turbine and the LNG-engine. The gas-turbine is more powerful and is in general a smaller component than the LNG engine. The gas-turbine system is more expensive than the LNG-engine, and so far, less efficient [18].

Since the principles for diesel engines and piston LNG engines are very simple, the same factors are affecting the efficiency. The Wärtsila 31DF can at maximum load achieve a thermal efficiency of 49% [30].

The most efficient stationary combined gas and steam turbines (COGAS) may achieve an efficiency up to 60% [22]. This is large and expensive steam turbines and they may not be suitable for various smaller ship designs.

2.3.4.2 Load Dependent losses

Since LNG CI engines are very similar to diesel CI engines, the same principles are valid here. If only thermodynamic efficiencies are considered, it is beneficial to have more than one engine to avoid only one load-curve. By doing this, more than one optimal load can be achieved. A possible system configuration for this set-up is shown in Figure 26.

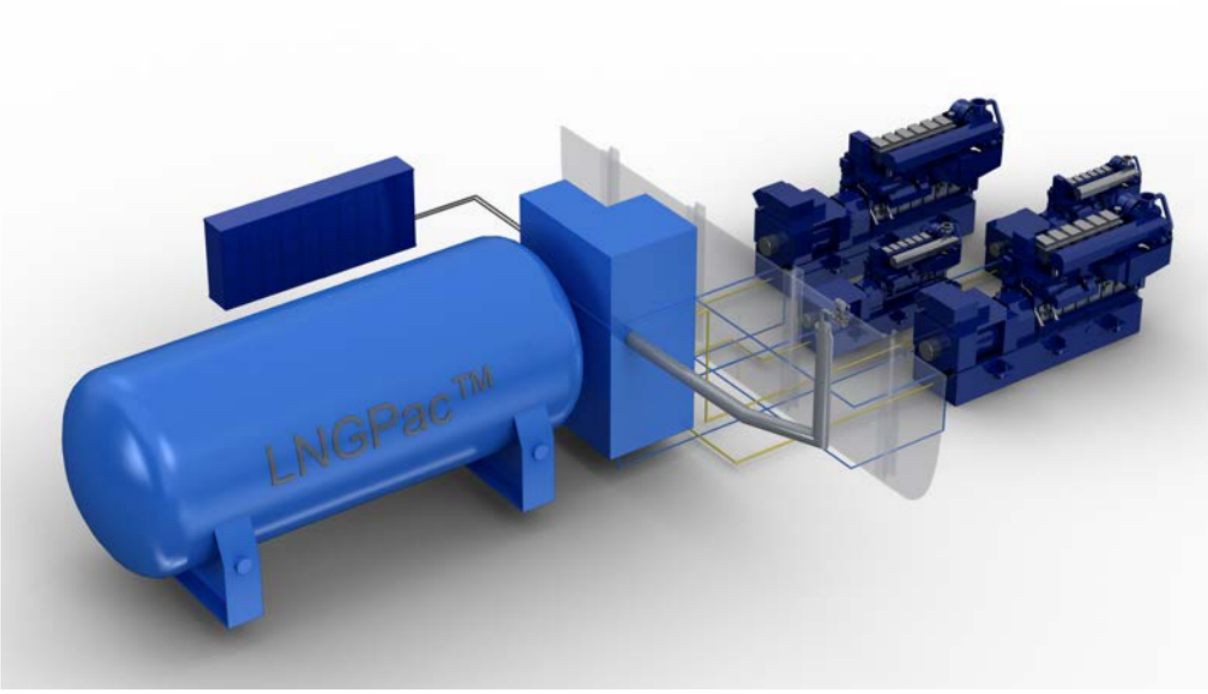


Figure 26 LNG engines connected to switchboard [31].

2.3.4.3 Fuel

LNG has a slightly higher lower heating value than diesel at 13.6 kWh/kg [32].

2.3.4.4 Emissions

The CO_2 emissions are reduced by 25% and the NO_x emissions are reduced up to 90%. The sulphur and particular matters are reduced up to 100% [32].

An issue with LNG combustion is that it represents a threat for CH_4 emissions. The impact on the climate by releasing CH_4 compared to for example CO_2 is 22 times worse. The reduction in CO_2, NO_x and other types of emissions may look better than they are if the emissions of pure CH_4 is high enough [2].

2.3.5 Batteries

The systems described in section 2.3.1-2.3.4 are all combustion engines retrieving energy from fuels. Energy storage through batteries is one of the most rapid increasing markets because of the focus at increasing the energy efficiency and reducing emissions. Both charging and discharging batteries can be done without emissions, and the processes are also energy efficient. To understand all the variables affecting efficiency in a battery, this section will present several battery technologies. The focus will be on lithium-ion batteries since this is the most common technology known in modern transport applications.

2.3.5.1 How Batteries work

A battery is a component used to store energy. It consists of one or several galvanic elements with a specific cell voltage. Every cell has one positive electrode, one negative electrode, an electrolyte and a separator to isolate the two electrodes. *Anions* are negative charged ions migrating to the negative electrode. *Cations* are ions charged positive migrating to the positive electrode. As illustrated in Figure 27, the electricity is produced when the electrons migrate from the negative electrode *(anode*) to the positive electrode *(cathode).* When the cell is producing electricity, redox is happening meaning that the electrochemical difference between the cells is decreasing. When the electrochemical potential is too low to produce usable electricity, the battery is out and need to be replaced or charged, dependent on the type of battery.

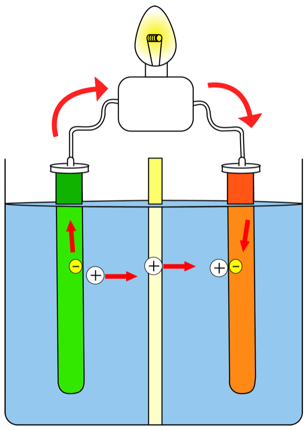


Figure 27 A Battery cell [33].

Battery cells can be connected in series or in parallel connections. By connecting all the cells in a serial connection, the cell voltage for each cell is added up to a battery voltage. By connecting the batteries in series, the voltage remains the same. Anyhow, the internal resistance decreases and therefore the potential current increases.

There are mainly two types of batteries, primary and secondary. Primary batteries are not designed to be charged, and the internal redox reaction is non-reversible. Secondary batteries are possible to reuse. In this master´s thesis primary batteries will not be discussed.

Secondary batteries consist of materials that can be reused, meaning that the redox-reaction is reversible. There are many different factors that affects the choice of type of secondary batteries. First of all, price is an important factor. Second, weight and lifetime are always crucial. There are also many other design-criteria´s that might be more or less important dependent on the purpose of the battery.

The first type of rechargeable batteries (secondary batteries) were the lead-acid battery. This was an open-air wet battery, used widely in automotive and maritime settings. Fully charged, the positive electrode consists of *lead-dioxide* (PbO_2) and the negative electrode of porous lead. Other secondary battery designs such as the nickel-cadmium-, nickel-zinc- and nickel-hydride-batteries have also been invented and are in use today.

The most known rechargeable battery is the lithium-ion battery. The reason why this is the most common, is the energy density and lifetime of this type. The lithium-ion battery can be used in different settings using different materials for cathodes and anodes.

A limitation for battery systems is the size and weight of the batteries as well as charge/discharge rates. Today, mostly ferries operating at shorter routes are considering batteries as the only power-source onboard [34].

2.3.5.2 Battery efficiencies

Even though the lithium-ion is the most common battery in autonomous and maritime applications today, there is a wide range of different products to choose in the design-process. Factors affecting the choice may be price, weight, lifetime, capacity and safety.

Lithium-ion is the lightest material with the highest energy density of the common battery materials. First, pure lithium was used as anode material, but the inherent instability of the lithium material made it non-reliable, and therefore the development changed its course toward lithium-ion anodes. There are anyhow at least four known cathode-materials with different properties [34].

- Li-Cobalt
- Li-Manganese
- Li-Phosphate
- NMC

The design of the battery assembly, the cathode used and the purity of the materials in the battery are all important factors to achieve the highest possible energy efficiency of the battery [34].

Designing a battery is a trade-off between weight, size, lifetime and time to charge. In general, the degree of discharge reduces the lifetime. This is shown in Table 2 and in Figure 28.

Table 2 DoD vs Cycles to 80% State of health for one of the systems delivered by Corvus Energy [35] .

DoD	Cycles to 80% SoH
80	6000
60	9000
50	14000
40	22000
30	41000
20	95000
15	160000
10	350000

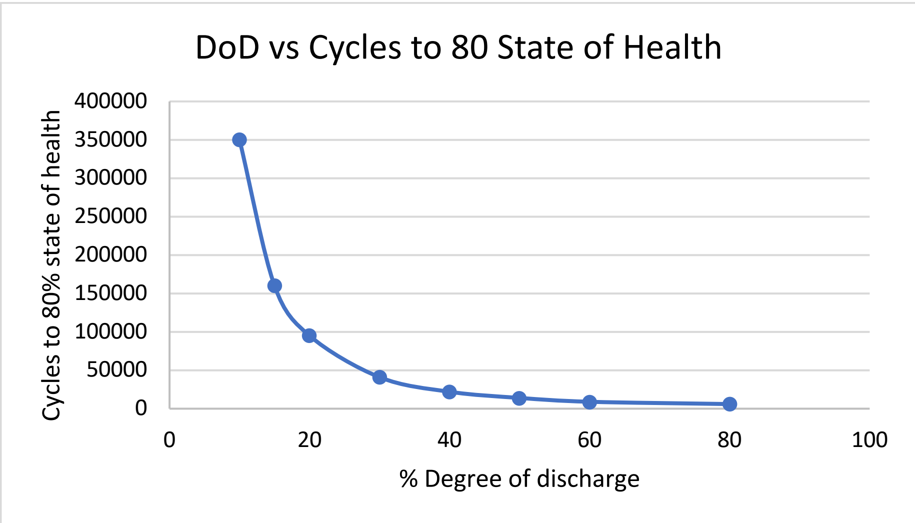


Figure 28 DoD vs Cycles to 80 State of Health [35].

In addition, the C-rate has to be considered when designing batteries. 1C corresponds to the power needed to charge the battery from 0% state of charge to 100% state of charge in 1 hour. 0.5C means that the battery will use 2 hours for the same operation, 2C means that the battery will do it in 30 minutes, and so on. The C-rate, the beginning of lifetime-losses and the end of lifetime-losses are all shown in Table 3 [35] [34]. For Corvus the end of lifetime for a battery is defined as the state were the battery capacity is at 80% of its original capacity.

Table 3 C-rate, Beginning of lifetime-losses and End of Lifetime-losses.

C-rate	BoL-losses, %	EoL-losses, %
0.5	0.7%	1.2%
1	1.3%	2.2%
1.5	1.9%	3.2%
2	2.6%	4.4%
2.5	3.2%	5.4%
3	3.9%	6.6%

Batteries has to be designed with some of the same losses as the systems described in the previous sections. The battery has to be connected to a switchboard and in some cases the power has to be ran through converters. All those losses have to be included when designing the size of the battery stack.

2.3.5.3 Load Dependent losses

In Table 3 the losses for charging the battery are shown. The losses for discharging the battery are the same. The DoD-cycle in Table 2 is also valid.

2.3.5.4 Emissions

Batteries are charged from the electricity grid. Given that the ferry is charged in Norway, the carbon footprint from charging the batteries is approximately 50 g CO_2 equivalents/kWh. Given that the battery is charged in a random harbor in Europe, the number is 558 g CO_2 equivalents/kWh [36].

In addition to the potential of emissions of emissions for the produced energy stored in the battery, the carbon footprint from buying and installing the batteries are important to recognize. It is difficult to estimate such variables, but 273 kg CO2-eq/kWh was estimated by Maritime Battery Forum in 2016 [37] .

2.3.6 Hydrogen Fuel Cells

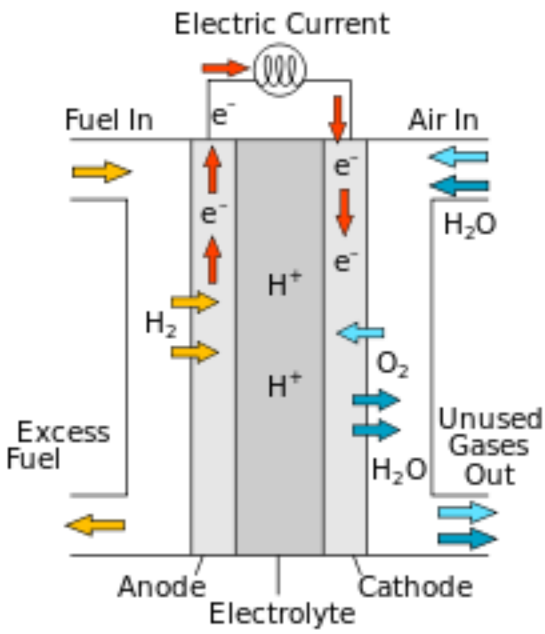
Not unlike the battery technologies described in section2.3.5, fuel cells use chemical processes to convert chemical energy to electricity. In this section, hydrogen, the different fuel cell technologies, efficiency of the fuel cell and load dependent losses of the fuel will be presented.

Hydrogen is the lightest of all elements in the periodic table. With its high energy density, it is also one of the most abundant atoms in the universe. Because of this, scientists and engineers have for a long time explored hydrogen as a suitable energy carrier.

There are several challenges with the physical properties of hydrogen. It is not only the lightest elements, but also one of the smallest. This leads to challenges with hydrogen-molecules migrating through pipe-walls and gaskets that could have been considered as tight. It is also highly flammable and energy demanding to produce.

The fuel cell is a component utilizing the electro-chemical potential difference between hydrogen and oxygen. The fuel cell consists of many of the same components as described in a battery in section 2.3.5, namely an electrolyte and two electrodes. Even though there are several types of fuel cells, most of them operate by the same principle. The hydrogen is introduced to the anode, where the hydrogen is stripped for electrodes and exists in an *ionized* form. The oxygen is led to the cathode, creating a *terminal voltage* like in the batteries. The electrolyte isolates the hydrogen atoms from the oxygen atoms, while an electrical wiring between the anode and cathode connects the molecules. The ionized hydrogen passes through the electrolyte, while the free electrons runs through the wiring making electric energy. A model to illustrate this is shown in Figure 29.

Figure 29 The Hydrogen Fuel Cell [38].



Hydrogen technology for autonomous and maritime applications are the least commercialized of the technologies mentioned in this report. There are five different fuel cells that are known and common:

- Alkali
- Molten Carbonate Fuel Cells (MCFC)
- Phosphoric Acid Fuel Cells (PFC)
- Proton Exchange Membrane (PEM)
- Solid Oxide Fuel Cells (SOFC)

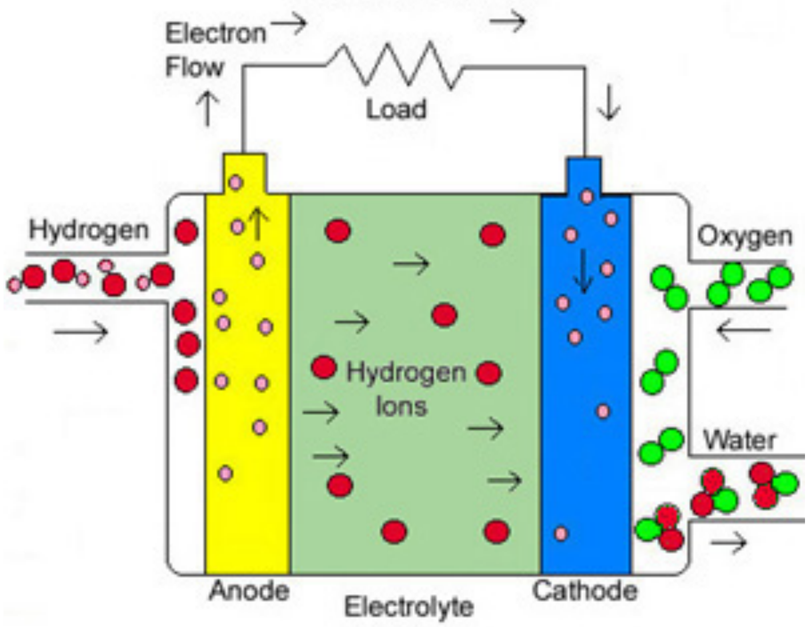
This paper will focus on PEM Fuel Cells and SOFC, since these two are the most considered technologies for maritime applications. This does not mean that MCFC, PFC or Alkali fuel cells are not relevant. [39]

2.3.6.1 Proton Exchange Membrane (PEM)

The PEM fuel cell is known as the most common fuel cell in modern applications. PEMs operates in the same way as the PFC. Figure 30 shows that the operation of the PEM and PFC can be compared to traditional battery technology. The PEM uses a cathode and an anode to exchange electrons from hydrogen to the oxygen through ionization of the hydrogen atoms. The electrolyte must be designed to only let ionized hydrogen through. Both in the anode and in the cathode, platinum is used as a catalyst to increase the efficiency.

During operation, the temperature in the PEM fuel operates at 80°C. The efficiency varies from 40-50%, according to the Smithsonian institute. A typical FEM fuel cell delivers 50-250 kW. The electrolyte in the PEM does not crack or leak, and the PEM fuel cell operates at a temperature that makes it suitable for smaller applications such as housing and automotive designs. The hydrogen-gas has to be purified to be used as fuel for the PEM, and together with the platinum catalyst, this increases the cost of the technology. [39]

Figure 30 Operation of the PEM fuel cell [39].

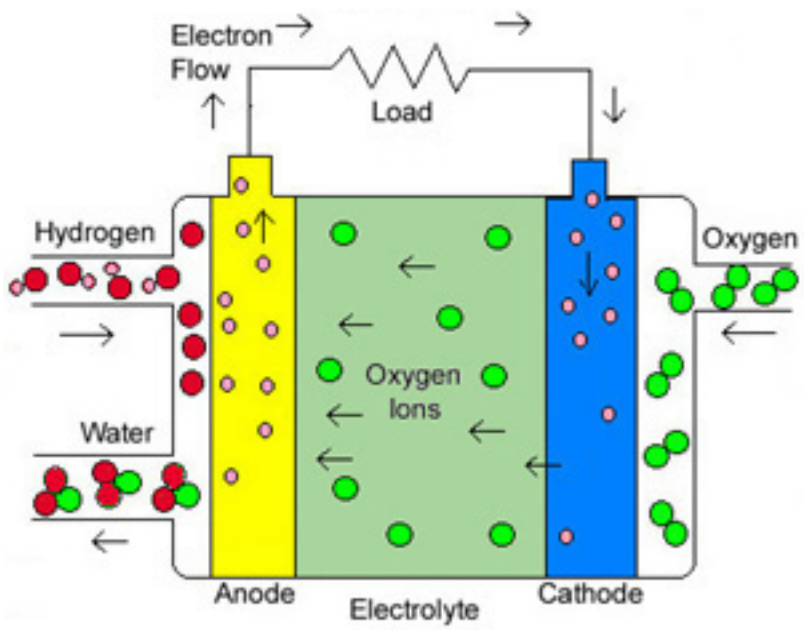


2.3.6.2 Solid Oxide Fuel Cells

The *Solid Oxide Fuel Cell (SOFC)* works a bit differently from the other four technologies mentioned above. SOFC has a solid ceramic compound oxide membrane. The ionized hydrogen is not sent through the electrolyte as in the PEM, but the oxygen is ionized with extra electrons in the cathode sending the oxygen through the membrane instead, as shown in Figure 31.

SOFCs operates at 1000°C and with about 60% efficiency [39]. The high temperature opens up the possibility for using heat recovery systems to produce additional electricity, hence increased efficiency. The SOFCs tend to be larger than the other technologies, which makes it more difficult to use them in automotive and trucks, but the increased efficiency makes them considerable in maritime applications. [39]

Figure 31 Solid Oxide Fuel Cells [39].



2.3.6.3 Load Dependent Losses

A fuel cell is not a rotating combustion engine as we know the diesel engine and the LNG-engine. Anyhow, it combusts hydrogen in a chemical process, with different efficiencies dependent on load.

Unlike most rotating combustion engines, the fuel cell is most effective at lower loads. As seen in Figure 32, the fuel cell increases rapidly from zero load to maximum efficiency and gets less efficient as load increases. The fuel cell is more efficient than the diesel engine for all loads and during some conditions more efficient than the LNG-piston engine from Wärtsilä. [39]

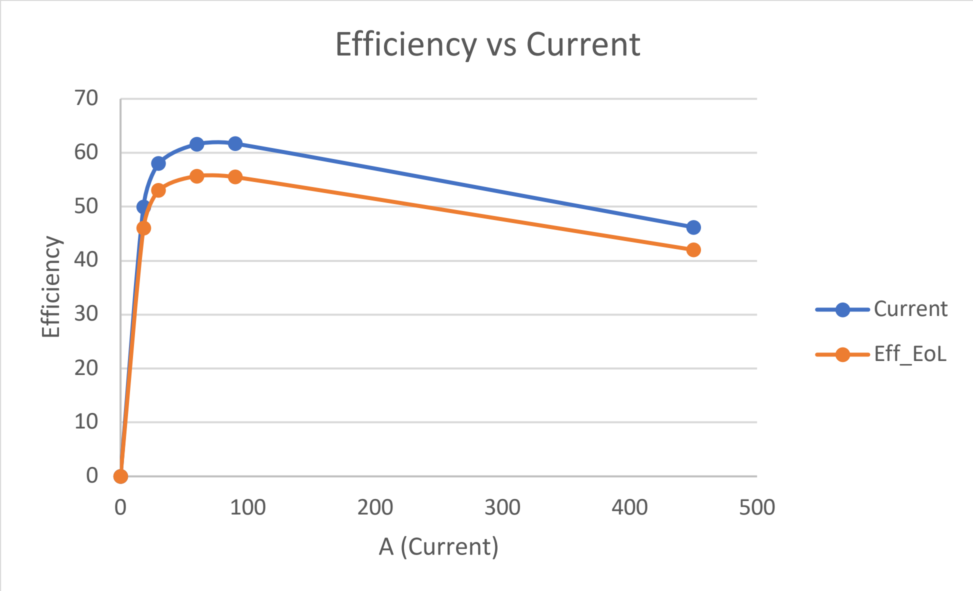


Figure 32 Load dependent losses for fuel cells. The values are estimations and not exact values. [40]

2.3.6.4 Fuel

Hydrogen can be produced through several methods. The most common production technique so far is through *Natural Gas Reforming*. This is not a renewable production method, but through carbon capture and storage (hereby CCS) the direct emissions from natural gas reforming can be avoided. The natural gas reforming process is so far the cheapest and most efficient way of producing hydrogen. Hydrogen can also be formed through coal in a process called *gasification*, but this process is less widespread. The majority of hydrogen in the international market is produced through natural gas reforming [41].

One of the biggest opportunities for hydrogen production in Norway is through electrolysis using parts of the available renewable energy. Even though *natural gas reforming* is a big opportunity given the big amount of natural gas available at the Norwegian Continental Shelf, the electrolysis potential of excess energy from Norwegian power production has to be considered. Electrolysis opens up for zero-emission hydrogen production. Anyhow, electrolysis is a more expensive and less efficient process than the natural gas reforming process. As a part of this project, the student went to Japan to visit several companies working with renewable energies. One of them, Toshiba, claims to be able to introduce electro to electro hydrogen systems with an overall efficiency of 80% [42] within a few years. If this is possible or not, is left to see. [39]

2.3.6.5 Emissions

In the previous section, reforming through natural gas was mentioned as one method of producing hydrogen. The hydrogen production through natural gas reforming can be described in the stages in Formula 34 and Formula 35.

Formula 34 first stage of natural gas reforming

$$CH_4 + H_2O = CO + 3H_2, \qquad \Delta H^o = 206\ kJ/mol$$

Formula 35 second stage of natural gas reforming

$$CO + H_2O = CO_2 + H_2, \qquad \Delta H^o = -41\ kJ/mol$$

By combing the two previous equations, we get Formula 36.

Formula 36 natural gas reforming.

$$CH_4 + H_2O = CO_2 + 4H_2, \qquad \Delta H^o = 165\ kJ/mol$$

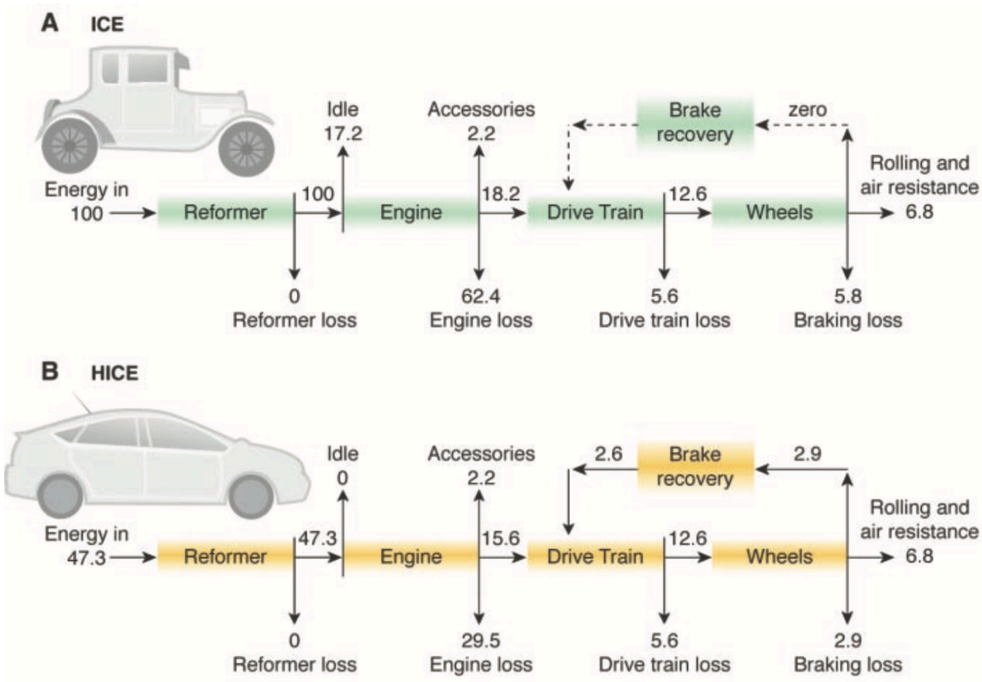
By using molecular-weight, the carbon/hydrogen production ratio can be calculated as a stoichiometric process to 5.5 kg CO_2/kg H_2 [43]. Because of the endothermic properties of the gas reformation, the real number is much higher. It is suggested that the representative carbon/hydrogen relation is as high as 9-14 kg CO_2/kg H_2 [43].

2.3.7 Hybrid Solutions

Hybrid systems compare two or more technologies to supply the energy demand for a system. Modern hybrid cars use batteries combined with for example an *otto*-engine or a diesel-engine. The purpose of this, is to increase the efficiency of the system and reduce the emissions. Hybrid solutions also opens up the possibility of peak-shaving, meaning that the peaks in an energy demand curve are supplied by a secondary power-source.

According to Nurettin Demirdöven et. Al. [44], hybrid solutions are suitable for recovering lost energy in automotive technology. As seen in Figure 33, Nurettin Demirdöven et. Al. claims that HICE car use 52.7% less energy than the ICE car. This is simply because of the idle loss and the breaking loss that are party recovered in the HICE car.

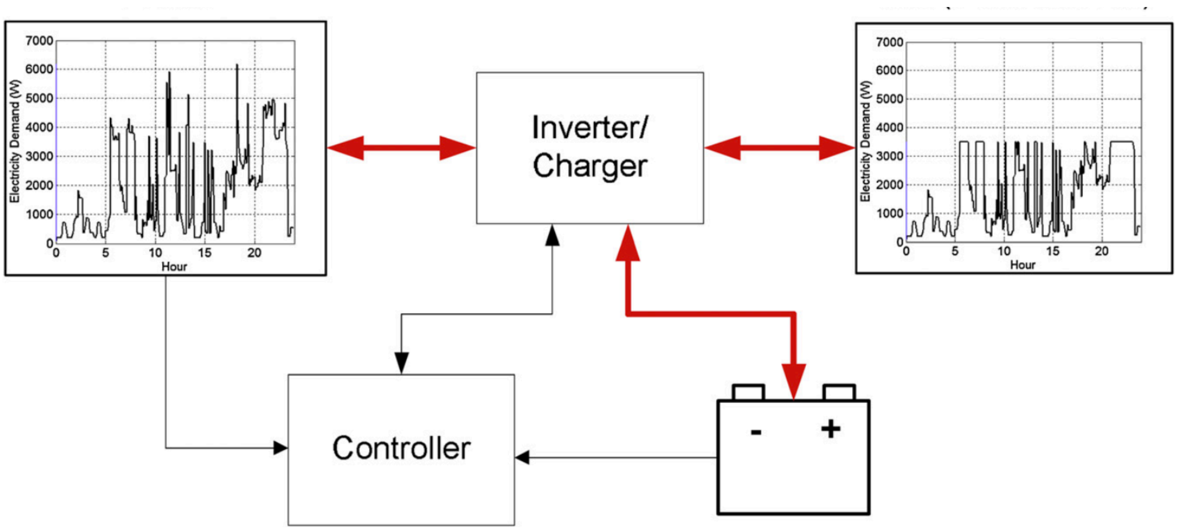
Figure 33 Efficiency comparison between Ignition-compression engines (ICE) and between Hybrid Ignition-compression engines (HICE) [44].



Peak Shaving of energy demand curves has received great interest the last decades. Peaks can lead to tremendous increases in costs. Designing a system to withstand the highest necessary load can lead to a low average efficiencies and increased emissions. According to Jason Leadbetter et. Al. [45], peak shaving can be used both in housing, automotive, maritime and aerospace. An example relevant for this master´s thesis may be a ship sailing from A to B. During this route, it mostly uses x kW. One day, the weather is really bad, which makes it necessary to use 1.4x kW to more the ship. If the ship is to be designed with a 1.4x kW powertrain, it will most likely not be as efficient as it would have been if it were designed to be peak efficient at x kW. Therefore, it can be beneficial both in case of efficiency and in case of emissions to use a battery package to supply the remaining 0.4x kW during the short peak period when it is necessary.

Peak shaving is illustrated in Figure 34. It is illustrated that during low peaks, the batteries are charged to be able to supply the system with energy during peaks. In this case, the peak demand is approx. 6100. Since the battery can supply energy during the peaks, the maximum electricity-demand from the energy source (may be a generator or an electricity grid) is approximately 3500W, while the battery supplies the additional 2600 W.

Figure 34 Peak Shaving system through hybridization of power-supply [44].



Another example of hybridization may be the design of possible zero-emission solutions with a traditional combustor backup. This is used widely in both automotive and maritime applications in modern technology. For cars, plug-in hybrids are models with the possibility of charging the battery package and run partly on electricity only from the battery. When the battery is discharged, an otto-engine or a diesel-engine takes over. For ships, it may be beneficial to enter urban areas or heritage sites running only on batteries. As shown in Figure 33, this also has a great impact on the idle losses from traditional fuel powertrains.

Hybrid solutions can be used in a wide range of applications, not only those mentioned above. During development of new energy solutions, like for example hydrogen powertrains, hybrid technology is used as a source of reliable power-supply.

2.3.8 Rest heat recovery

Rest Heat Recovery or *Waste Heat Recovery* has a great potential in increasing the thermal efficiency of heat engines. In most combustion processes, losses are represented by heat. This heat is in most cases released to the air, but it is also used for heating. If there is warm steam/water or air left after the heating is completed, it is possible to utilize this in waste heat recovery systems [46].

To calculate the heat recovery potential is a complex operation. According to Alfa-Laval, they are capable of providing energy savings of up to 14% [46]. This is again dependent on the specific ship design and the potential of utilizing the heat for purposes like hot water production, heating, de-icing and etc. The cost of the systems also plays an important role in the overall design.

2.4 Costs

In section 2.4, the report will focus on methods used for calculation of the costs related to changing from traditional powertrains to alternative, more efficient and possibly renewable fuels.

In the following sections, the difference between *operational expenditures* and *capital expenditures, inflation, interest, discounting, cashflow* and *lifetime costs* will be presented.

2.4.1 Operational expenditures and capital expenditures

Operational expenditures, or *opex,* are funds used for the daily operation. These are costs that are running constantly and may vary dependent on the operation. Food, fuels, energy, working clothes and insurances may be examples of operational expenditures. They are not considered to be investments but running costs in the day-to-day operation.

Capital expenditures, or *capex*, are outlays used to invest in or maintain an asset necessary to maintain the overall operation. In the case of this project, capex is represented by the cost of buying the engine and the funds necessary to replace it if useful life is expired.

Investing in an engine results in a negative cashflow but is considered to last for more than one year, hence capex. Buying fuel is also a negative cashflow but it is expected that fuel costs are necessary costs through the year to run the operation, hence opex. Yearly maintenance may be operational expenditures while maintenance done every fifth or tenth year may be classified as capital expenditures. [47]

2.4.2 Inflation

In general, costs are increasing. This meaning that the level of prices for goods and services is rising. Income and salaries are also increasing. This means that the purchasing power of money is failing. Buying an engine that costs for example 10 MNOK today may not be as expensive in five years even if the price in numbers remains the same.

Inflation has to be considered in budgeting to include the expected level of costs in the future.

According to *Norges Bank* [48] the inflation target in Norway is 2%. The European Central Bank "aims at inflation rates of below, but close to 2% over the medium term" [49] [47].

2.4.3 Discounting

To find the value of an investment necessary next year in the present value, discounting is necessary. Discounting is done by implementing the interest rate of an investment. The interest rate is the sum of cost of dept and the rate of return for the lender.

If the discount rate is assumed to be 2% ($\delta = 0{,}02$) [50] [51] then the discount factor is defined as in Formula 37.

$$\rho = \frac{1}{(1+\delta)} \approx 0{,}98$$

Formula 37 The discount factor. δ is the interest rate. [52] [47]

The present value of a cashflow, N_t, made in t years is therefore found by using Formula 38.

$$N = \rho^t N_t$$

Formula 38 The present value, N, of a cashflow N_t in year t given the interest rate ρ. [52] [47]

2.4.4 Cashflow

To find the present value of funds used in year T as shown in Formula 38, a cashflow has to be forecasted. This meaning that all funds used in year T has to be summarized to be discounted.

Since the two types of expenditures studied in this master´s thesis is operational expenditures (*opex)* and capital expenditures (*capex)* then the cashflow in year T is simply as in

$$N_t = opex + capex$$

Formula 39 Cashflow in year N_t. [47]

2.4.5 Lifetime costs

If all capex and opex are found and discounted to the present value, an estimate of lifetime costs $N_{lifetime}$ can be found simply by Formula 40.

$$N_{lifetime} = \sum_{t=0}^{t=T} \rho^t N_t$$

Formula 40 Lifetime cost of the system based on cashflows in future years. [47]

3. Approach

In section 3, the methods used in this master thesis is presented. The chapter will explain how the tool was developed, how calculations were implemented and how field studies were used to improve the tool.

The following sections will first cover the tool interface design, then the mathematical and numerical construction and build-up of the tool and in the end a report from the field trip at NFT Steigen.

3.1 Mathematical and numerical construction of the tool

This section explains how the calculations for the different fuel- and engine types used in the tool are made. The build-up of the tool and the variables are shown in Figure 35.

The tool is built up by four disciplines of inputs; Ship design, Operational Study, Engine Setup and Cost and Assembly. Each category consists of two types of inputs, simple setup and advanced setup.

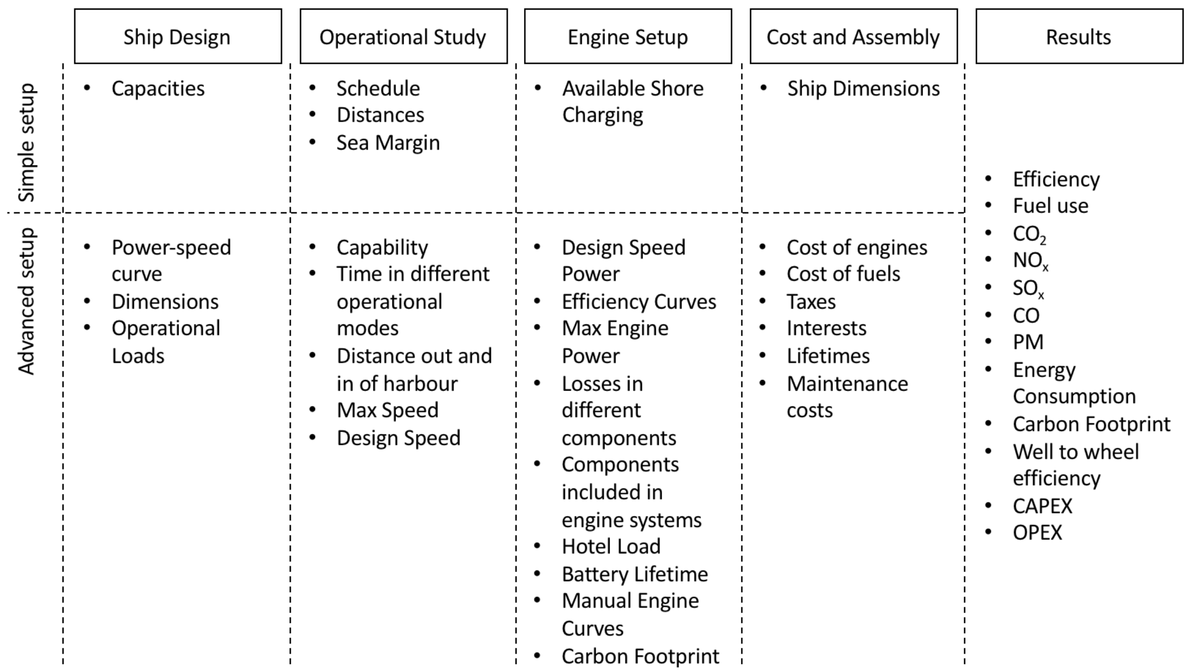


Figure 35 Build-up of variables in the tool.

In the following sections, the design and the mathematical connection between the variables in Figure 35 is explained.

3.1.1 Ship Design

The first inputs found in the tool are related to the ship design. In the tool, the first decision taken is what type of ship this is, hence which tool you choose to open. Then the user defines the amount of goods transported. For a passenger ship the unit used is passengers, for a car ferry the unit is number of cars and for the live fish carrier the unit used in this tool is m^3 tank capacity. The default values are based on the selected ship type and capacity.

In following sections, the necessary ship design calculations and variables are presented.

3.1.1.1 Power-speed curve

The Power-speed curve is confidential and valuable information for most ship designers and ship owners. An effort was made to sample data from the largest companies running double-ended car ferries in Norway, but due to confidentiality, the data were not shared with the student. Contracts signed by county councils for operation of car ferry connections today are mainly based on costs, emissions and engine performance.

Because of the missing data for power-speed curves from modern ship designs, the student had to look into already published research and articles to find representative values to use as predefined values. In a report made for Statens Vegvesen by LMG Marin several values were found. These values are presented in Table 4. Anyhow, these values only represent the power needed to run the ferry in 12 knots with a given capacity, and not dimensions, operational loads and etc. Because of missing information about operational loads, the student estimated these with help from Havyard Design and Solutions AS. The values chosen are not representative for Havyard Designs but only expected values for similar designs. The values inserted can be found in the tool in datasheet cell A1:AI9.

Table 4 Car capacity vs power. PBE stands for "Personbilenheter", passenger car units. Ship dimensions were not described.

Capacity	Power-speed [12 knots]	Power per car
20 PBE	504 kW	25 kW/PBE
30 PBE	510 kW	17 kW/PBE
40 PBE	584 kW	15 kW/PBE
50 PBE	602 kW	12 kW/PBE
70 PBE	684 kW	10 kW/PBE
120 PBE	700 kW	6 kW/PBE

Since the operational loads and dimensions are unavailable for the user, a 120 PBE car ferry has been used as a reference in the double-ended car ferry tool, a 3250 m^3 live fish carrier for the live fish carrier tool and a 700-passenger cruise ship for the passenger vessel tool. The three selected ship´s data are not based on precise performance data from Havyard Design and Solutions AS but market trends and consultancy from R&D Manager Kristian Steinsvik. For the double-ended car ferry, the capacities in Table 4 has also been added to the library.

To find the exact theoretical power-peed curve for calm water performance, advanced simulation tools and experience with hydrodynamics and ship design is crucial. Since the field of study for this master´s thesis not is to find the representative power-speed curve, it is prepared for manual inputs for the actual power speed curve. This can be found under "Ship Design" in Predefined variables/functions.

If the power-speed curve is unknown, the user has two options; the user can use one of the predefined hulls that are selected and hence the auto generated *"Design Speed"* and *"Design Speed Power"* both found in Sheet B1, or manually add an expected *"Design Speed"* and *"Design Speed Power"*. *"Design Speed"* are found under Route Studies in sheet B1 and *"Design Speed Power"* are found under Engine Setup in the same sheet.

Based on *"Design Speed"* and *"Design Speed Power"* the project has used the Admiralty coefficient to find a power-speed curve. According to Kristian Steinsvik in Havyard Design and Solutions AS the actual Power Speed Curve often varies a lot from the Admiralty Coefficient curve [9]. The Admiralty Coefficient formula is shown in Formula 41.

Formula 41 The Admiralty Coefficient relating design properties to requested properties.
∇ stands for deplacement, P for power and V for velocity.

$$A = \frac{\nabla^{\frac{2}{3}} \cdot V^3}{P} = \frac{\nabla^{\frac{2}{3}}{}_{des} \cdot V^3{}_{des}}{P_{des}}$$

The power-speed curve can be found in Sheet D. All the calculations are done in the Data Sheet under Admiralty Coefficient Calculations. The admiralty coefficient presented in section 2.1.5 has been used to find the power for each speed with a 1 knot step interval. Nonlinear regression, the LINEST function in excel, has been used to find a third order equation. This is the power-speed curve used if automatic setup and predefined variables are used. The possible choices are shown in Figure 36.

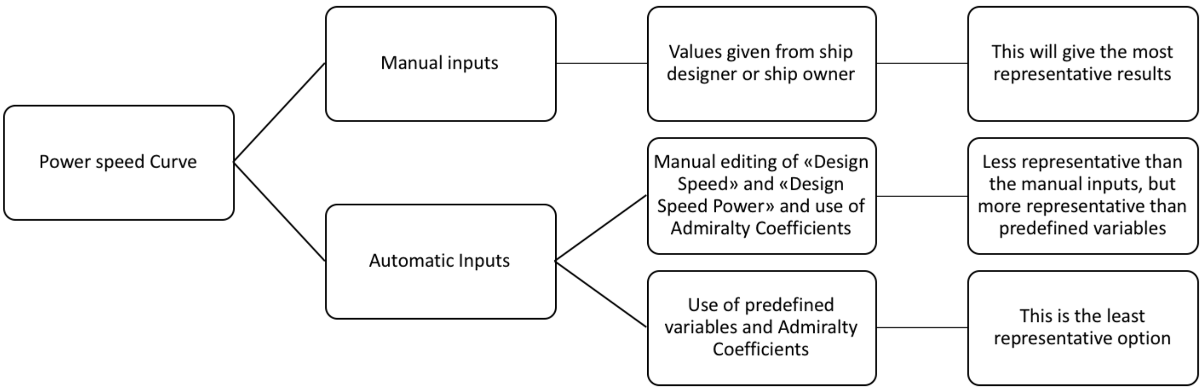


Figure 36 Possible choices for power-speed curves.

As seen in Formula 41, the displacement is also a component in the admiralty coefficient. This means that the weight can be related to increased power. According to Kristian Steinsvik in Havyard Design and Solutions AS, this is also not necessarily representative. An example of this is that increased displacement in some cases may lead to increased capabilities and hence lower power consumption. For simplifications, the admiralty coefficient is anyhow used in this tool to possibly show increased power consumption due to increased weight. This can be important to for example show if increased weight due to use of batteries instead of generators can have an effect on the power consumption.

To find the new power the displacement of the ship has to be known. Therefore, it is necessary to fill in the *"Deadweight"* and the *"Lightweight"* columns in Sheet B1. It is important that the new weight, has to be without the weight of the engine, the fuel and the other components not necessary to run battery systems. If the values are not filled in, the increased power due to weight is not included. The formula is used in the data Sheet under power consumption calculations for batteries as a function of increased weight compared to the diesel, LNG and Diesel Hybrid systems. The weights of the batteries, the engine and the fuel are also presented in Sheet E. The added resistance due to increased weight function is so far only added to the propulsion for ferries.

3.1.1.2 Operational Loads

Some vessels have several operational procedures that are repeated in their work. For a live fish carrier, lice treatment, pumping and other operations are common procedures not necessary dependent of speed. For passenger ferries and car ferries, leaving harbor, entering harbor, acceleration and other operational procedures are situations that are very common and need to be considered.

To include these operations in the analysis, it is important to know the power consumption during these loads. There are predefined variables in the data sheet in cell A1:AI9, but to make an exact result, it is necessary to fill in these values manually based on data from ship owner or ship designers.

The operational loads are either automatic based on the ship archive or manually added in advanced setups.

3.1.1.3 Dimensions

Dimensions are included in the tool only for informative purposes. Except for the lightweight and the deadweight used in the admiralty coefficients as explained in section 3.1.1.1, none of the variables are explanatory variables.

Dimension inputs are automatic and based on the ship archive or manually added in advanced setups.

3.1.2 Route studies

To analyze how the ship is expected to be used, route studies and operational studies are included in the tool. The purpose of route studies is to present the expected operational configuration for the ship. This including how many hours through the year or through the day that the ship is in operation and what kind of operation it is in. An example of this is shown in Figure 37. If the operational loads are known as described in section 3.1.1.2, it is possible to calculate the expected energy consumed given that we have the information in Figure 37.

In general, all variables important to analyze the operation of the ship has to be included in this section. This includes for example distance sailed, time and distance for acceleration and retardation, sea margin, capabilities, design speed and max speed.

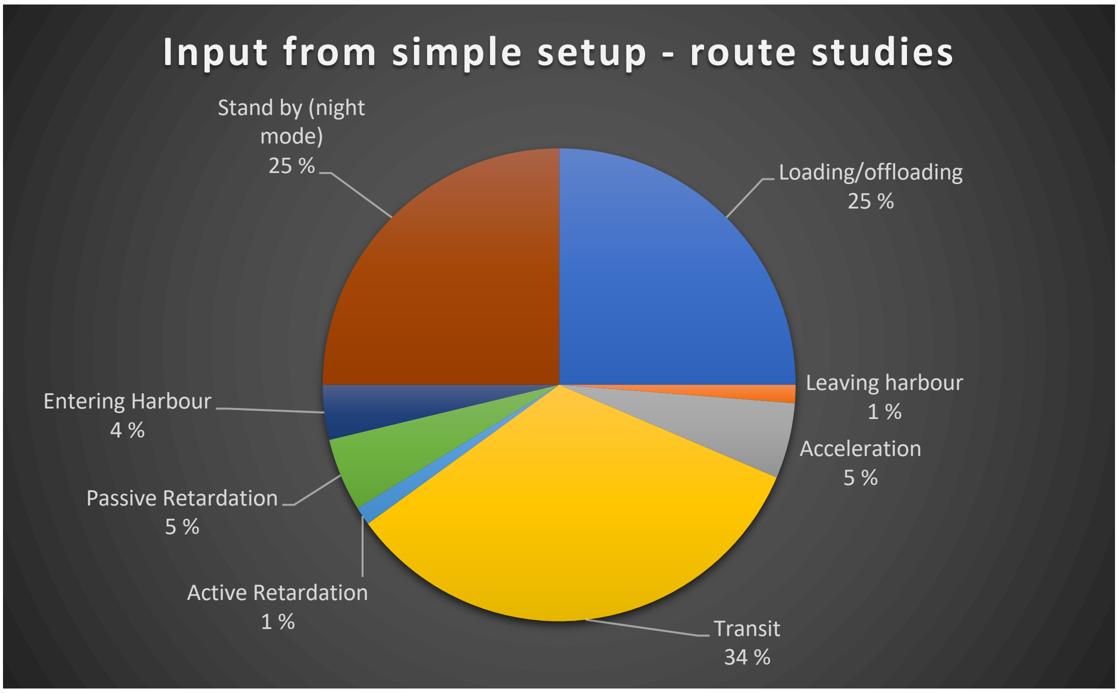


Figure 37. Percentage of operation. Example from a double-ended car ferry.

In the follow sections, the report will present how the tool handles the operational study of the design, how sea margins and capabilities has been included, how battery dimensioning has been done according to the route studies, how maneuvering operations such as entering harbor and leaving harbor has been taken into consideration and how the other operational factors has been included.

3.1.2.1 Operational Study

The three types of ship studied in this master´s thesis operates under different circumstances. A double-ended car ferry and a cruise ship/passenger vessel both operate time schedules that are important to follow, and leaves and enters harbor more than one time per day. A live fish carrier on the other hand, does not necessarily operate at a fixed time schedule which makes the operational study a bit more complex.

For the passenger vessel and the double-ended car ferry, the tool has taken into consideration the time that is needed to sail from A to B, and hence the speed that is necessary to reach harbor in time. Car ferries sailing between no more than five ports can be analyzed in this tool. Figure 38 shows how the simple setups for the car ferry version of the tool looks like. First, the number of ports has to be chosen. Later, time in each port, distance from port 1 to port 2 and transit time can be selected. The preset max speed is 16 knots (this can be edited in sheet B2). If the speed necessary to run the ferry from one port to the next exceeds 16 knots, the “Is this less than the max speed?” cell will turn from “Yes” to “No”.

Figure 39 shows how the advanced setups for route studies are done. In this section, the time used for the maneuvering operations are taken into consideration. In addition, the distance needed to maneuver the ferry out and in of port are included.

In the datasheet the speed needed to run the ship according to the schedule is calculated. Together with the power-speed curve, this represents an energy demand for the propeller.

Route Study

	Unit			
Number of ports	n	3	Max Speed With Current Schedule	15,9 knots
			Is this less thant the max speed?	Yes
			Are there sufficient charging for batteries?	Yes

	Shore Charging [kW]	Time in port [min]	Transit to next port [min]	Distance to next port [nm]
Port 1	5000,00	10,00	20,00	4,00
Port 2	5000,00	10,00	19,00	4,00
Port 3	5000,00	10,00	22,00	4,00

	Unit	
Number of roundtrips per day	n	18,00
Sea margin level [Serice Area]	1,2,3,4	1
Capability level [Serice Area]	1,2,3,4	3

Figure 38 Simple Setups for route studies for double-ended car ferries.

Route Studies

Capability	70,00 %	Sea Service Area Margin	5,00 %	Minutes in port	258
				Minutes at sea	1182

Time in different ports [s]

	Shore	Loading	Entering harbour	Leaving Harbour	Acceleration	Passive retardation	Active retardation
Port 1		600	90	30	124,00	120	30
Port 2		600	90	30	124,00	120	30
Port 3		600	90	30	124,00	120	30

Design speed	12,00 knots	Distance for maneuvring	0,7 nm	Max Speed	16 knots

Figure 39 Advanced setups for route studies for double-ended car ferries. The minutes in port and minutes at sea are just for indicative purpose.

Ideally interviews of operators and users of car ferries, passenger vessels and live fish carriers would have to be carried out to make a proper route study of ships in operation. Since this project is limited in time, interviews were done of three officers operating NFT Steigen and one officer from another company (Sølvtrans). These interviews can be found in appendix E.

3.1.2.2 Maneuvering

The time necessary to accelerate the ship to the necessary speed, slow down the ship before entering port and the time used for off- and on-loading has to be taken into consideration when calculating consumptions for most ships. In this master´s thesis, it is assumed that for the versions tailored for a car ferry and a small cruise ship, the process of entering and leaving port represents a larger percentage of unit time and therefore consumes enough time to be analyzed in detail. Therefore, these processes are more advanced for these tools. An example of necessary inputs for a car ferry is shown in Figure 39.

By interviews of crew onboard live fish carriers, these inputs are found less important. Since most live fish carriers leaves and enter harbor fewer times than a passenger vessel and a car ferry this input is removed in this version to simplify the tool.

Another reason why time in port is important to analyze for cruise ships and car ferries is to learn more about the possibility for using batteries.

3.1.2.3 Sea margin and capability

In this tool, sea margin represents the necessary multiplication factor needed to give a representative result given the weather condition the ship is going to operate in. Since the power-speed curve is calculated based on a calm water performance prognosis, added resistance has to be included as a result of wind, waves, current and other factors that increase the power demand. The sea margin is the *average* multiplication factor. This meaning that in some cases the margin will be less and, in some cases, higher, but for the purpose of calculating the average power consumption, the sea margin is used.

Capability is used to calculate the maximum performance for the ship. If the engine has to be sized to operate the ship under harsh conditions, a bigger engine is needed.

Both capability and sea margin are based on four levels. The corresponding % of multiplication is shown in Sheet E and are predefined editable. These are presented in Table 5.

Sea margin are multiplied with necessary propeller power for each operation in route studies. The capability factor is multiplied with necessary engines size, further explained in section 3.3.

Table 5 Sea Margin and capability multiplication factors.

Level	Sea Margin [%]	Capability [%]
1	5	20
2	12	40
3	18	70
4	40	100

Sea Margin and Capability can be edited in sheet E – Route Studies. If the ship is to be used in areas with very extreme weather conditions and the capability need to be satisfying these conditions, it is recommended to change the values for capability and sea margin in sheet E.

3.1.2.4 Battery dimensioning

For the cruise ship- and car ferry versions the preset battery dimensioning is simply based on the available shore charging and time in port. For a live fish carrier, this is a bit more complex. Since a live fish carrier often operates a range of fish farms, the operation may vary a lot. Therefore, a design operation has been included in this version. The thought behind this is to study if the live fish carrier can be run by batteries for a requested operation. The *Design Route* inputs can be found under route studies in Sheet B1 for simple inputs. Note that this is an optional selection that can be excluded if batteries are not considered.

For the double-ended car ferry, the battery dimensioning is based on expected lifetime, shore charging and time in port. It is also possible to enter a maximum capacity for the batteries in sheet B1. For simplifications it is assumed that batteries are used during transit and not for maneuvering for the hybrid engines.

Figure 38, presented earlier in section 3.1.2 shows the route study inputs for double-ended car ferries. If one of the charging-stations in port delivers too little energy to run the ferry to next harbor, the tool will change the “Are there sufficient charging for batteries?” from “Yes” to “No”. The user then knows that the available shore charging is too small. Similar answers can be found in the passenger ferry versions as well. This is explained in appendix D. Instruction Manual.

3.1.3 Engine Setup

Now that the ship- and route studies are completed, the energy demand variables to be used for engine performance calculations are prepared. In Figure 40 it is hierarchically presented how ship design and route studies are used to find the energy demand, which is described in the previous chapters. In this section, the energy demand will be used as inputs together with the engine performance prognoses to find representative consumptions and emissions.

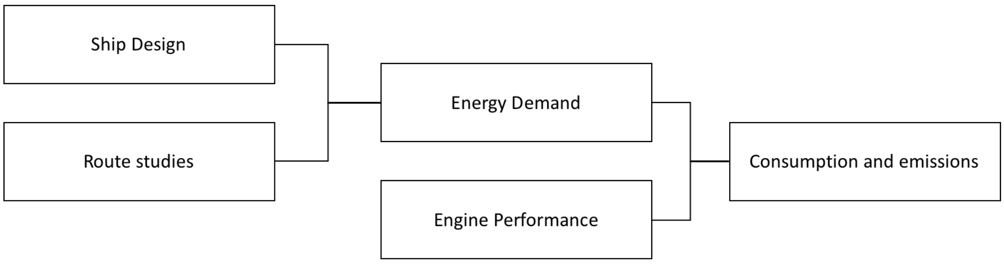


Figure 40 Ship design, Route studies and engine performance are necessary inputs to find the consumptions and emissions from the ship.

The following sections will describe how component losses are included in the tool, such as switchboard-losses and cabling losses, how fuel curves are used to describe the performance for mechanical powertrains for LNG and Diesel fuels, how hybrid solutions are implemented for diesel, LNG and hydrogen powertrains and how performance predictions are made for battery and hydrogen powertrains.

3.1.3.1 Component losses

A power system is based on several components acting together to supply the necessary energy to the ship. Section 3.1.3.1 will present the components acting outside the break efficiency of the engine, this meaning cabling, switchboards, etc. The components internal losses have to be included in the calculations.

The losses from powertrain components can vary from design to design. This can for example be because of different lengths of the cables between the generator and the propellers in a diesel-electric power system, limited cooling possibilities and other factors. Therefore, all versions of the tool have the possibility of changing the loss factor in the different components. It is also possible to activate or de-activate component losses.

Figure 41 shows how the setup for component losses is implemented in the tool. First, the type of component has to be revised for propulsion and for electricity in advanced inputs in Sheet B2. The component setups are the same for all of the engine types. Next, the component has to be activated or de-activated for every engine type. This is done in Sheet F, Engine Setup. The % loss per component is predefined but can be changed. This is done in Sheet B2 for advanced Setups. Note that all component losses are predefined but editable.

The tool will show a % loss for the system (exclusively the break engine efficiency) for all the different power systems. This can be used to learn more about different powertrains efficiency.

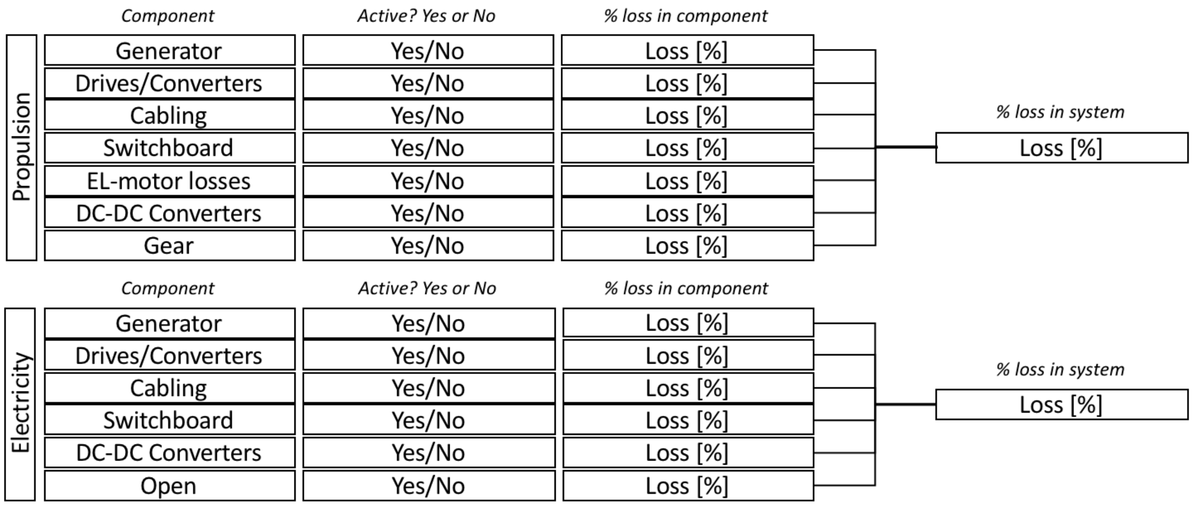


Figure 41 Component losses in the system. Component setups and % loss in component is the same for all the systems and the selection where the component is activated or de-activated and the % loss in the system is different based on engine type.

For the losses related to electricity production and distribution, there is an "open"-cell where component losses not included in the tool can be added. This is done simply by editing the open column in the advanced inputs sheet, adding a %-loss and activating it in the engine setup sheet.

The preset losses that are listed in Table 6 are based on interviews from Senior Designer Electro Kay Lorgen in Havyard Design and Solutions and Product Manager Michael Odland from Norwegian Electric Systems. Interviews are found in appendix E.

Table 6 Component Losses. These are based on interviews found in Appendix E.

Generator	Drives/ Converters	DC/DC Converters	Switch-board	El-motors	Gear	Cabling
5%	5%	5%	3%	5,9%	5%	5%

3.1.3.2 Thermodynamic Efficiency of engines

For all engine types adopted into this tool, thermodynamic efficiency is maybe the key performance indicator. Dependent on engine load, a thermodynamic performance is found through testing.

When designing a ship, the load dependent losses curve tested by the manufacturer of the engine is necessary to design the powertrain. If the most efficient powertrain consists of a single two stroke diesel engine with diesel mechanic propulsion line or several generators connected to a switchboard in a diesel electric powertrain varies from ship to ship and from operation to operation. Some customers even demand that more than one engine have to be running for safety reasons.

By combining several engines in a powertrain, a more efficient powertrain can be achieved. This can be explained by studying a ferry. Its operation consists mainly of maneuvering operations in and out of port and transit operations between the ports. During maneuvering, more engine power may be necessary to achieve sufficient capabilities, this meaning that we may only use 40% of the engine power during transit and 80% during maneuvering. If the engine´s maximum thermal efficiency is 80%, it may be more economic- and fuel friendly to install two engines. This opens up for the opportunity for using one engine running at its 80% load during transit, and two engines running the overall systems 80% load during maneuvering operations.

In theory, it can in some cases be useful to exploit almost an unlimited number of engines to achieve a maximum efficiency at all useful loads. In practice, available space, cost, maintenance, operability and human factors makes this impractical. Anyhow, it is very difficult to state a standard efficiency curve for engines for any ship design. By combining all setups available from Pon Cat, Rolls-Royce and Wärtsilä, we have a very high number of possible configurations for engine setups.

In the tool there is predefined load dependent losses curves to make it possible to use without further knowledge of engine performance curves. The state-of the art engines used as references for these predefined variables are listed in Table 7.

Table 7 Reference types for the different fuel types. LNG provided relative performance per load per cylinder, therefore there is no Power listed for LNG Constant RPM. The max power for battery stacks is not relevant.

	Diesel Variable RPM	Diesel Constant RPM	LNG Constant RPM	Hydrogen Fuel cell	Battery stack
Make	Pon Power	Pon Power	Wärtsilä	Hydrogenic	Corvus
Type	3516C	3516C	W31 DF	HD120	E2450-V1
Power [kW]	2350	2350	NA	120	NA
Contact	Pål-Erik Ruen	Pål-Erik Ruen	Dirk Folchert	Mark Kammerer	Geoff Crocker

The efficiency curves for the selected engines can be found under engine setup. The engine curves are editable so that the user can use his own engine curves if necessary.

For *hydrogen fuel cells*, the engine performance curve looks a bit different than the fossil fuel engines. The two fuel cells studied in this master´s thesis are designed and produced by *Hydrogenic* and *Powercell and* both of them have a peak efficiency at lower loads. Since one fuel cell itself rarely is enough to run the ship, it is assumed that all fuel cells are started and loaded at peak efficiency before the load of each cell is increased.

In the tool, it is prepared for variables representing peak efficiency load, peak efficiency, max load of each fuel cell and a performance curve from peak efficiency to max load. A graph representing a typical fuel cell can be found in section 2.3.6.

For *batteries* the performance is not calculated the same way as for fuel cells or fossil fuel combustors. The key efficiency indicator for batteries is the C-rate. The producer tests the battery and can estimate which loss that are related to the specific C-rate. Variables necessary to calculate battery performance is expected lifetime, the different operational loads, number of charging cycles and necessary capacity.

Density and energy content of the fuels is important variables for determining fuel consumption for engines. The values used in the tool is presented in Table 8.

Table 8 Density and Energy Density of fuels

	Energy Density [kWh/kg]	Density [kg/dm^3]
Diesel	11,97	0,855
LNG	13,69	Not used
Hydrogen, liquefied	39,4	0,7
Hydrogen, compressed	39,4	0,22

To summarize how thermodynamic efficiency of a ship is calculated Figure 40 can be used. By using the ship design and the power-speed curve combined with route studies, a one year or one day operational profile of the ship with representative energy demands can be found. If these demands are used as inputs to the engine performance curves, consumption of fuel and energy use can be found.

3.1.3.3 Hybridization

This section contains some of the same explanations as in section 3.1.2.4. This is because the important information about shore connection and time is found under route studies.

Three of the engines studied in the tool are hybrid solutions, namely Diesel Constant RPM (Diesel-Electric), LNG Constant RPM (LNG-Electric) and Hydrogen. There are two purposes of hybridization that are focused on in this project; one where the aim is to reduce the overall engine size by adding batteries and one where the purpose is to charge the batteries while the ship is in port to reduce load on the engine in parts of the tour.

3.1.3.3.1 Live fish carrier

For the live fish carrier, the focus of the hybridization in this tool has been to use charging capacity from shore to run the ship. The reason for this, is that a live fish carrier often utilizes most of the engine capacity only for integrated systems and not for propulsion. This meaning that the average relative load is higher than on for example a car ferry. Small battery packages can be used for peak shaving, but to estimate the effect of this can be difficult and is very dependent on the specific efficiency loss for the engine when exposed to changing loads. It has on the other hand been prepared for an option where the effect of a given % of battery energy used per tour can be analyzed. This input is found in sheet B1 for simple inputs.

For hydrogen solutions, the hydrogen system is designed to handle the engine by itself. It is anyhow important to note that it is beneficial to have a battery package onboard to handle the peaks in load. It is not possible to consider charging batteries from land for the live fish carrier hydrogen solution. The tool will need further work to make this possible.

3.1.3.3.2 Car ferry and passenger vessel

For the car ferry and the passenger vessel version of the tool, available shore connection has been used to optimize the batteries. This meaning that the possible charge based on charging capacity and time in port has been used to dimension the battery. The charged energy is assumed used during transit, hence the relative load from the diesel engine, the LNG-engine and the hydrogen fuel cell is less than it would have been without the charge.

If one port does not have charging capacity, the tool will notice this and assume that the engine has to supply all the necessary energy.

As described in section 3.1.2.4 there is an opportunity for defining the max size of the battery. If the ferry is in port for a longer time the battery will be designed to charge the whole period. By using maximum battery size, this can be avoided.

3.1.3.4 Emissions

Standards have been used to calculate emissions in this tool. There are several available standards. For CO_2 estimations the Norwegian national standards have been used [25]. For NO_x, CO, PM and SO emissions, IMO tier standards have been used. The predefined emission factors can be found Table 9.

Table 9 Emission factors for diesel- and LNG-engines.

CO_2 per kg fuel, kg	NO_x per kWh, g	CO per kWh, g	PM per kWh, g	SO per kWh, g
3,17	7,85	5	0,5	1
3,17	7,85	5	0,5	1
2,76	1,5	5	0,005	1

CO_2 is different from the other emissions since it is measured based on mass of fuel used. The other exhaust gases described in this tool are all based on kW consumed.

All emissions factors are predefined and based on data from IMO Tier 2 and Pon Power. They are anyhow editable and can be found in sheet B2 – advanced inputs.

3.1.3.5 Carbon Footprint

Carbon footprint for production and storage of fuels are included in the tool. The predefined factors for carbon footprint estimations for diesel, LNG and electricity are found in sheet F – Engine setup [2].

For future work it is relevant to analyze the footprint from the engine itself.

3.1.3.6 Well-to-wheel efficiency

There are no predefined inputs for well-to-wheel efficiency. These inputs will have to include the energy loss from production and storage of fuels. To reach the global energy efficiency target this is an important measurement.

The tool is prepared for well-to-wheel efficiency inputs in Sheet F – Engine Setup.

3.1.4 Cost

To calculate the costs of an engine for a ship can be done simply by adding all the costs related to the powertrain. So far, the tool has calculated an energy demand and used the engine performance calculations to find consumptions and emissions. Now that numbers for fuel consumption and engine data is available, these can be used to calculate the costs (Figure 42).

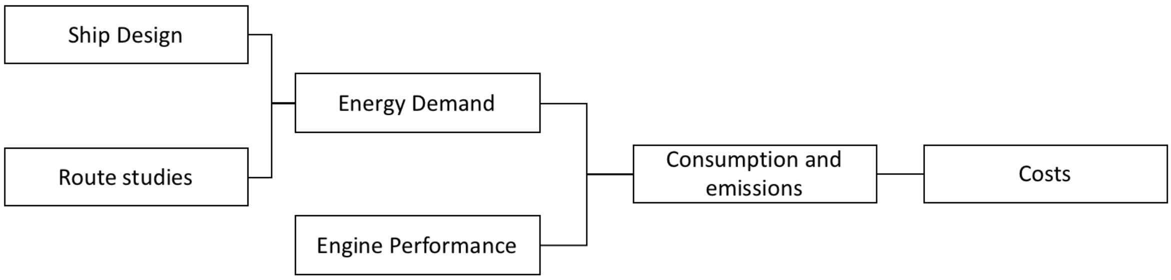


Figure 42 Hierarchically build-up from ship design, route studies, engine setup and costs.

Doing engine costs analysis in a general form is complicated. All systems are dependent on fuel tanks, different energy transformers and control systems. To make the tool as simple as possible, the student has focused on installation costs per kW/kWh, costs per kWh for fuels, expected lifetime for the system and yearly maintenance (opex) per kW/kWh. If the user of the tool has a broader knowledge in costs for the systems, all values are predefined but editable. The cost-analysis build-up of the tool is shown in Figure 43.

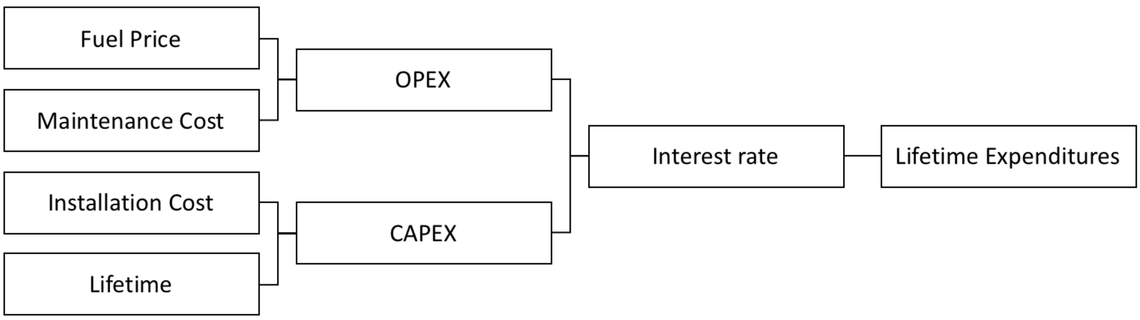


Figure 43 Build-up of the cost analysis of the different fuel systems for the tool.

In sheet G in the tool all cost calculations can be found. The four variables fuel price, maintenance cost, installation cost and expected lifetime are predefined but editable.

3.1.4.1 OPEX

There are two different formulas used for opex calculations in the tool. One for non-hybrid systems and one for hybrid systems.
For powertrains consisting of one type of engine Formula 42 can be used. Engine size is the calculated max power of the engine in the tool in kW, and yearly maintenance costs are given as a function of the max power. Yearly maintenance costs are predefined as 0 in the tool but is an open input that the user can define if necessary.

Energy use are defined as the energy used in kWh. That means the lower heat value of the fuel consumed. The energy costs are given in kr/kWh.

$$OPEX = (Engine\ Size \ \cdot Yearly\ Maintenance\ cost) + (Energy\ use \ \cdot Energy\ cost)$$

Formula 42 OPEX calculations for non-hybrid powertrains.

For hybrid systems, all types of engine used has to be calculated in the tool. Therefore, the tool uses Formula 43 for hybrid system calculations when there are n types of engines used.

$$OPEX = \sum_{n=0}^{n=x}(Engine\ Size_n \ \cdot Yearly\ Maintenance\ cost_n) + \sum_{n=0}^{n=x}(Energy\ use_n \ \cdot Energy\ cost_n)$$

Formula 43 OPEX calculations for hybrid systems.

3.1.4.2 CAPEX

For capex calculation of the tool, engine size, cost per size and lifetime are the only inputs. It is assumed that the ship has a lifetime of 20 years. In year 1 (in finance year 0 would have been used) an investment is always made with a negative cashflow to buy a powertrain. The powertrain has a given useful lifetime, and when the time is passed, the system has to be replaced.

In the tool, logical "IF"-functions has been used. If we assume that lifetime can be denoted by L and time since the system was bought are denoted by t, a new system has the be bought every time *t* exceeds *L*. If we also assume that N_t (N is the product of engine size and cost per kW) is the investment made to buy a new system, we can use Formula 44.

$$IF(t > L)\ THEN\ (N)\ IF\ NOT\ (0)$$

Formula 44 Logic function for engine costs.

If it is a hybrid system, t, L and N has to be used for all available systems and calculated.

3.1.4.3 Summarizing life cost estimations

When all capex and opex are found, they are summarized discounted and summarized again according to Formula 40. The results are presented in a graph in sheet G and numerically in sheet C.

3.1.4.4 Important predefined values

To find estimations for life time costs for the different fuels there are several predefined values that are used. Energy cost (kr/kWh), installation cost (kr/kW), Lifetime expectations and maintenance cost per year (kr/kW) are listed in Table 10. All these estimates are based on market trends and direct contact with suppliers, customers and others.

Table 10 Predefined values for energy cost, installation cost, lifetime and maintenance.

	Energy cost [kr/kWh)	Installation cost [kr/kW]	Lifetime [years]	Maintenance [kr/kW)
MGO	0,58	3000	20	0
LNG	0,58	10000	20	0
Hydrogen	2,28	13000	3	0
Batteries	0,57	5460	10	0

3.2 Tool Interface

The tool is designed to be simple, possible to use for people with different experience, user friendly and usable without having access to advanced computer software. It is designed in Microsoft Excel since that is a common software in the Microsoft Office package. Several other programming codes and software were also considered, this is explained further in appendix C.

To make it simple to generate reports and to read important numbers such as carbon emissions or costs, the interface for the three different ship designs were designed to be similar. In Figure 40, the different sheets in the tool is shown. In this case, it is the passenger ferry version that is presented.

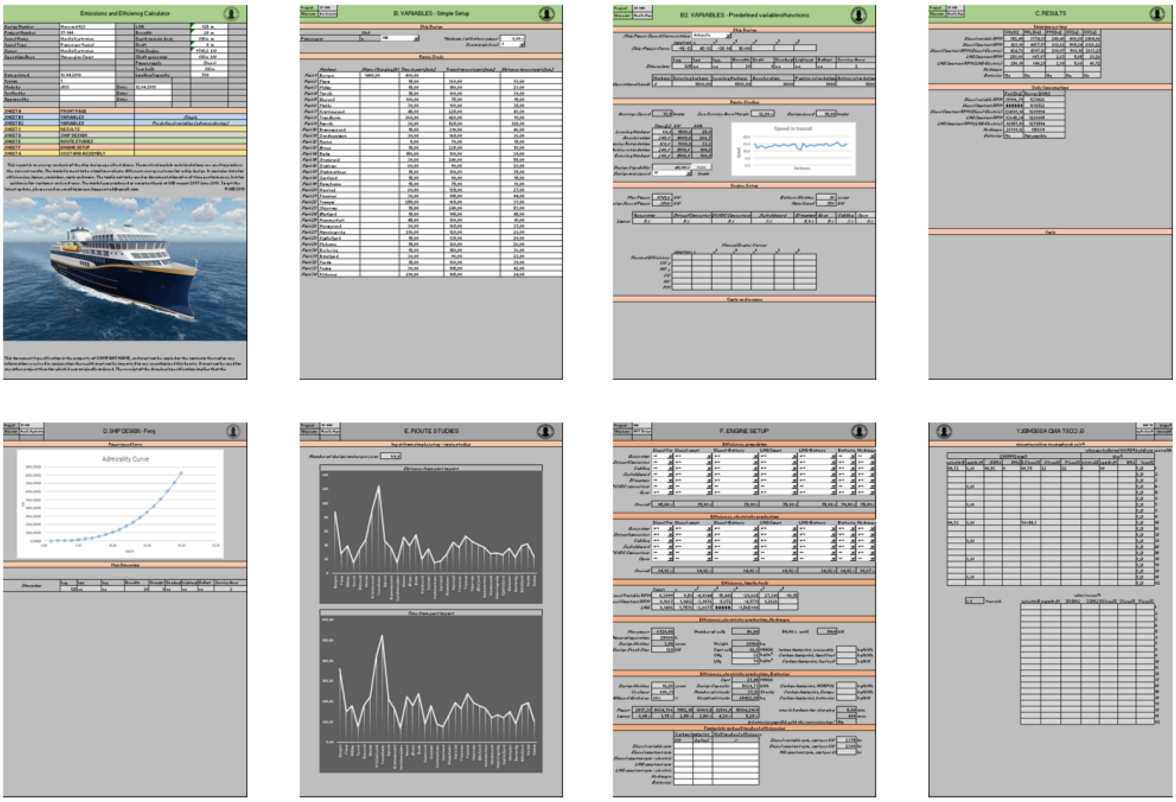


Figure 44 Tool Interface.

In Table 11, the different sheets are listed in the same order as in Figure 40. The simple inputs in sheet B1 will always have to be filled in to produce a result. If the user needs a more precise result and has sufficient data to fill in all the predefined variables in sheet B2, the result will be more precise. There are also editable variables in sheet C-F that can make the result even better.

Table 11 Sheet build-up in the tool.

Sheet A	Sheet B1	Sheet B2	Sheet C	Sheet D	Sheet E	Sheet F	Sheet G
Frontpage	Simple Inputs	Advanced Inputs	Results	Ship Design	Route studies	Engine Setup	Cost and Assembly

To make it simple to know what inputs that are predefined, which ones that are not predefined and what is results, three different colors has been used. These colors are shown in Table 12.

Table 12 Color coding of necessary inputs, predefined inputs and results, text or indicators.

Necessary inputs	Predefined inputs	Results, text or indicators

In order to make the tool understandable for everyone and possible to use without further knowledge of ship technology, emissions, engines or anything else that is studied in this master thesis, editing only simple inputs is sufficient to produce a result in sheet C. Therefore, all predefined variables had to be added by the student.

By only inserting simple inputs to the tool, it is expected that the possible error in the result is very high, because of all the variables that are predefined. By also editing the advanced inputs, such as ship power-speed curve and engine efficiency curve, possibly the error gets smaller. By adjusting all the parameters in sheet B-F, the goal is to achieve an error less than 5%. This is illustrated in Figure 45.

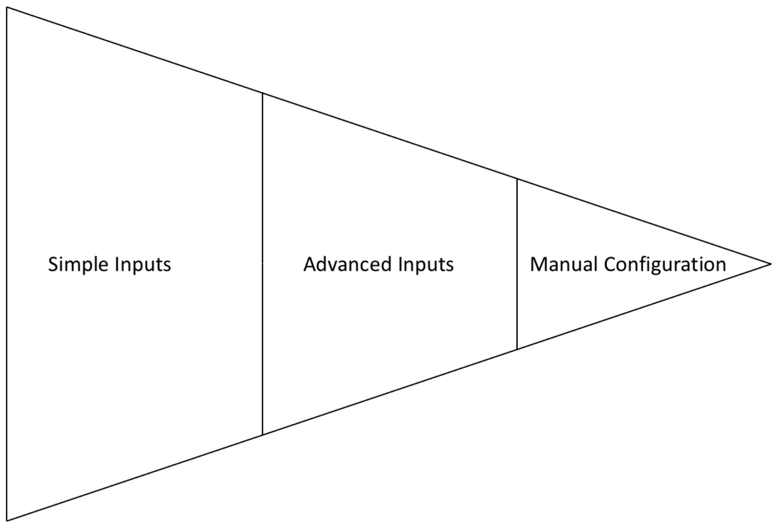


Figure 45 The more inputs the user provides, the smaller the expected error gets.

The last sheet in the tool is the "Data" sheet. This is where all the predefined numbers from the suppliers are used and where all the calculations are made. The user does not have to make any changes in this sheet, and when the report is generated, this sheet is not included. The only reason why a user should make changes in this sheet, is to enter values for predefined ships.

Visual Basic programming is used to make buttons and pull-down selections in the three different versions of the tool. The codes are not attached to this report but can be found in the tool.

Appendix D represents a user guide for the tool. It is made one user guide for all of the three versions, with explanations for the different setups.

3.3 Study Trip to NFT Steigen

To study the functionality of the tool and learn more about live fish carriers in operation, a visit was arranged onboard NFT Steigen. Several interviews were made to try to learn more about the operation of the ship and the different factors affecting the energy consumption. By studying the real-life load curves for the engine and the route passed, the aim was to compare this to the route study model in the tool.

3.3.1 Havyard 587 specifications

The first days onboard the ship was in the port Bodø. That made it possible to make interviews, take pictures and study the engine configuration of the ship without disturbing the crew and operations.

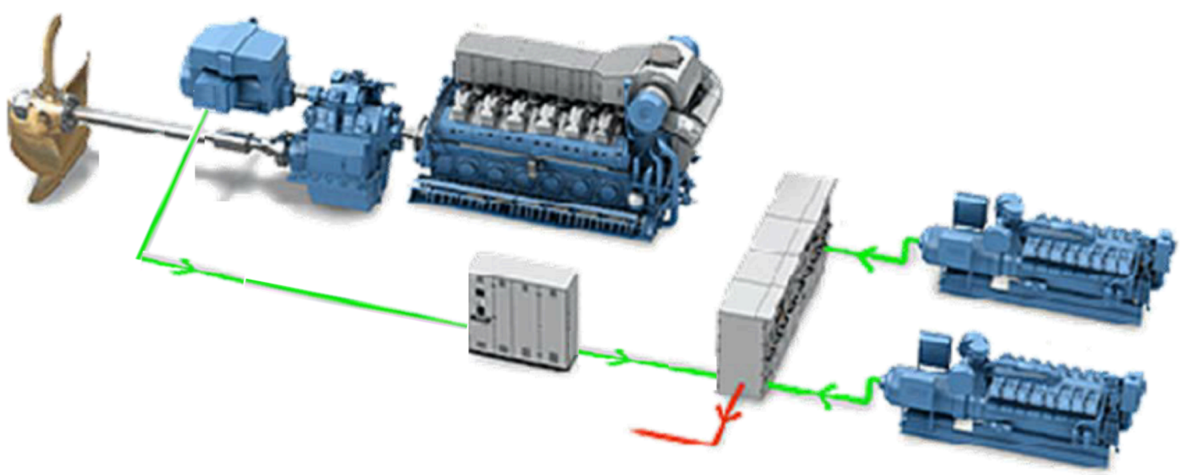
The powertrain consists of the components shown in Figure 46. The system in the figure is designed by Rolls-Royce Marine AS. The system onboard NFT Steigen is not delivered by Rolls-Royce Marine AS but has the same build-up.

A main engine is connected to the propeller through a gearbox. The gearbox is connected to a shaft generator through a clutch. The main engine can therefore both run the propeller and the shaft generator at the same time. To change the speed of the ship, the pitch of the propeller blades or the rpm of the engine as to be changed. The most common way to run the engine is by running it at constant rpm and only change the propeller pitch. When the pitch is changed, the load at the engine varies. To ensure the correct frequency at the shaft generator, this engine can´t be connected to the shaft generator while running at variable rpm.

Two generator sets are also placed onboard. The purpose of these are to supply the ship with more electricity if necessary. There is also a harbor generator not shown in this figure. The purpose of the harbor generator is to supply the ship with sufficient hotel power while ship is in harbor.

The powertrain is design to run the live fish carrier as efficient and with as low fuel costs and emissions as possible.

Figure 46 Rolls-Royce Hybrid Solution. This has the same build up as the one onboard NFT Steigen.



In Table 13 the main dimensions for NFT Steigen are listed.

Table 13 NFT Steigen dimensions.

Year built	LOA [m]	Breadth [m]	Draft [m]	DWT [t]	Capacity[m^3]
2017	84,8	16,9	6,5	4150	3200

The ship is currently at a long-term contract for Cermaq Norway AS. It was not working for its contractor at the time the project visited the ship but instead doing sub-lease jobs for other customers. Therefore, it was expected that the operational profile for the ship was slightly different from the profile it will enter when working only for its main contractor.

3.3.2 Questions

The student had prepared a question form to interview officers maneuvering the ship. The questions asked are listed below.

i. During a one-year period. Please suggest 10 operational modes that are significant either because of the amount of time the ship is in that mode or because of the energy consumption during that mode.

ii. For the ship-type that you have been asked to represent, please answer the following:
- What do you think are the three most energy demanding modes?
- What do you think are the three less energy demanding modes?
- Do you think there is a significant difference between energy consumption for ships dependent on the officer in charge at the bridge?
- Most likely, the answer to question 2.4 is that in some operations yes, and for other operations no. Please comment which modes that are energy demanding and which modes that are not.

iii. Is there any focus at reducing fuel costs and emissions during operation?
iv. Do you see any potential ways of cutting fuel costs during operation?

3.3.3 Operational monitoring

To learn more about the operational profile monitoring where an important part of the study trip. Are there any differences between the operation and the energy load dependent on the officer on the bridge?

4. Results

In section 4 the results obtained from the tool when applied to the specific use cases for the passenger vessel, car ferry and the live fish carrier are presented. In addition, measurements from NFT Steigen are shown and compared to the modeling outputs.

The results are divided in three main sections based on the three following keywords:

I. Energy
II. Emissions
III. Costs

4.1 Passenger Vessel

The passenger vessel studied in this master´s thesis is similar to the ones operating along the Norwegian coast in the route named *"Kystruten Bergen-Kirkenes"*. Available AIS data through www.marinetraffic.com [53] together with route information from *Hurtigruten ASA* [54] has been used to define the route.

4.1.1 Energy

Figure 47 and Table 14 shows the representative energy consumption per tour from Bergen to Kirkenes based on engine type for the Havyard 923 Passenger Vessel. As seen, Hydrogen and LNG-Hybrid (in that order) are the most efficient powertrains. Batteries are more efficient than hydrogen but not possible to use with the technology available today because of factors such as charging time and weight.

Table 14 Consumptions for the Passenger Vessel sailing from Bergen to Kirkenes.

Consumptions per tour					
	Fuel [kg]	Energy, fuel [kWh]	Energy, electricity [kWh]	Used [kWh]	Incl WTWE [kWh]
Diesel variable RPM	105854	1267076		1267076	NA
Diesel Constant RPM	108794	1302258		1302258	NA
Diesel Constant RPM (Diesel-Electric)	123236	1475129	33950	1509079	NA
LNG Constant RPM	85574	1189702		1189702	NA
LNG Constant RPM (LNG-Electric)	83616	1162896	33950	1196846	NA
Hydrogen	27848	1130628	33800	1164428	NA
Batteries	Na		558775	558775	NA

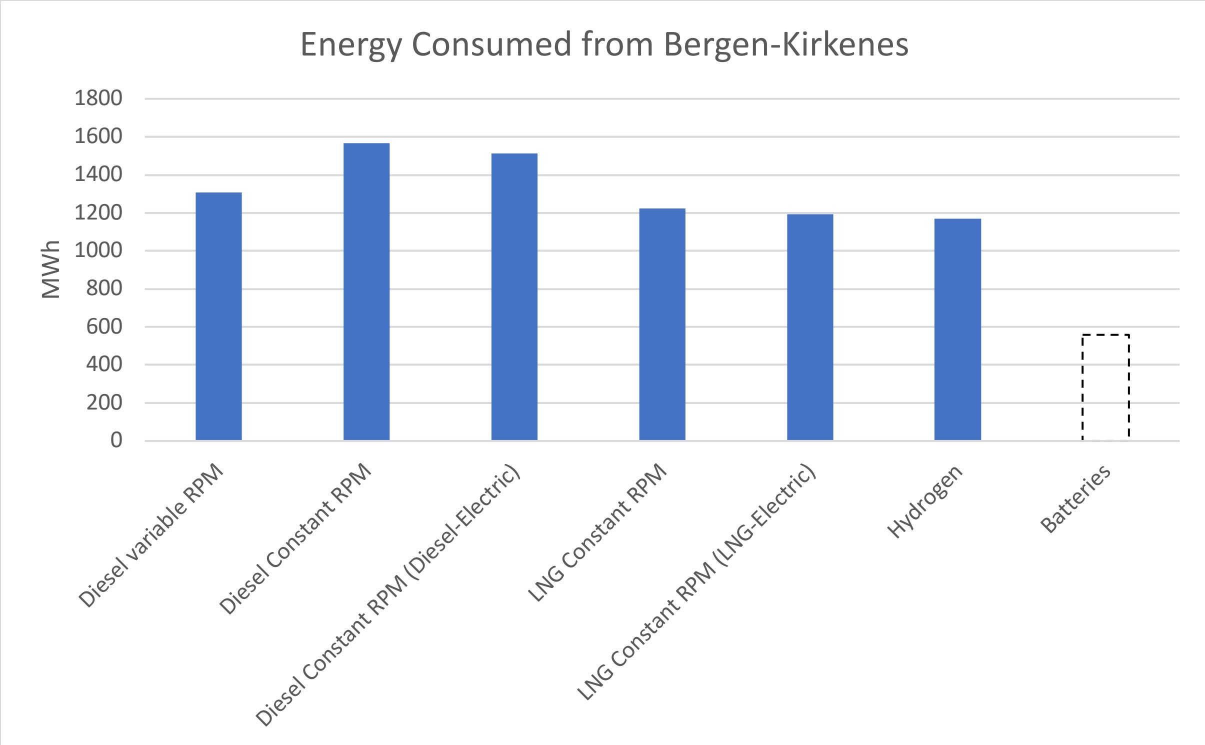


Figure 47 Energy Consumption for the Havyard 923 Passenger Vessel. Hydrogen is the most effective of the energy carriers. The numbers are based on an analysis from the tool analysis found in appendix A. Batteries are not possible to consider with the technology available today.

4.1.2 Emissions

Figure 48 and Table 15 shows the CO_2-emissions from combustion of the fuels for the engine. Diesel-solutions represents the most CO_2 polluting solution, LNG about 25% less than Diesel and no CO_2 is released into air from the combustion of hydrogen usage of batteries.

Figure 49 and Table 15 presents the CO_2 footprint from combustion of fuels and production of fuels. The tool does not consider the footprint from production and maintenance of the different powertrains. When footprint is considered, we can see that Hydrogen and Batteries also has a carbon footprint.

Figure 50 and Table 15 shows the NO_x emissions from the fuels. Diesel is the most polluting one while LNG only pollutes a small percentage of NO_x compared to Diesel powertrains.

Figure 51 and Table 15 represents the other particles and gasses released by burning fuels. Diesel is the most polluting while LNG only represents a smaller part of the same gases.

Table 15 Emissions for the Passenger Vessel sailing from Bergen to Kirkenes.

Emissions per tour							
	CO_2 [t]	NO_x [kg]	PM [kg]	SO [kg]	CO [kg]	Carbon Footprint [t]	
Diesel variable RPM	336	3662	233	466	2332	378	In addition comes the emissions from producing the engine. These are not included in the calculations
Diesel Constant RPM	345	3662	233	466	2332	388	
Diesel Constant RPM (Diesel-Electric)	391	4203	268	535	2615	441	
LNG Constant RPM	236	826	3	6	28	271	
LNG Constant RPM (LNG-Electric)	230	803	3	5	36	266	
Hydrogen						96	
Batteries	Na	Na	Na	Na	Na	28	

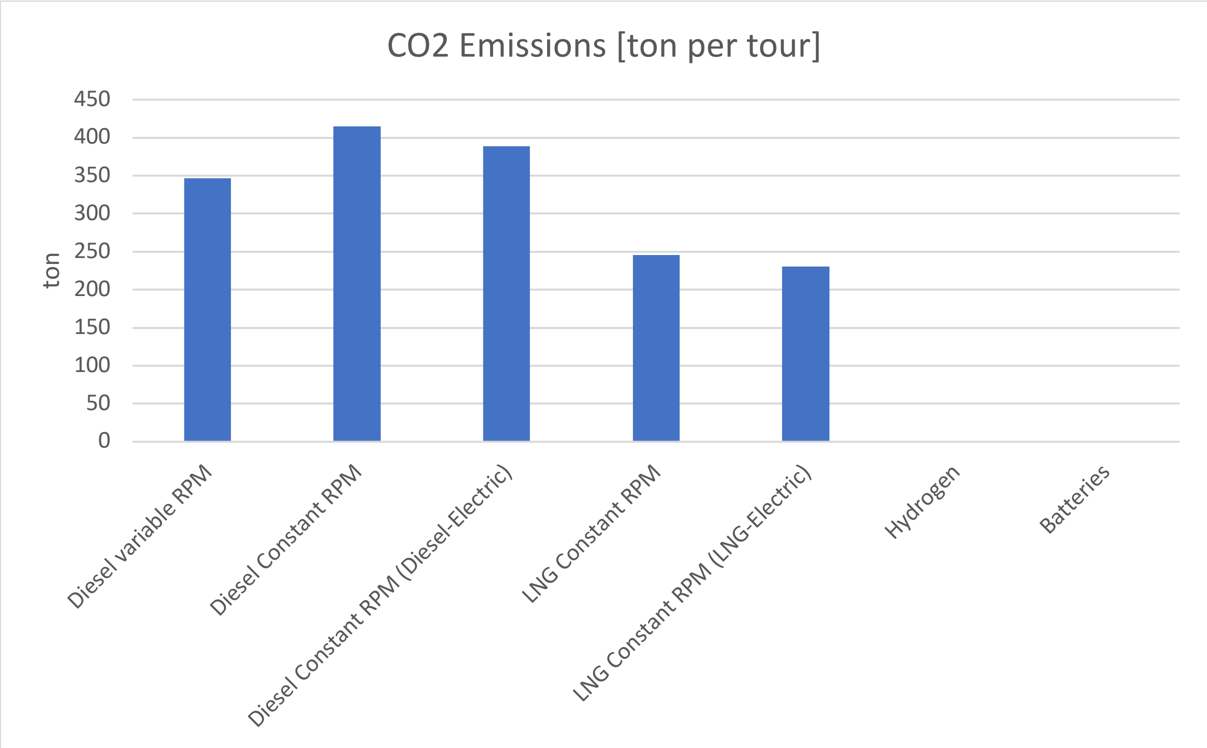


Figure 48 CO_2 emissions in ton per tour for the Havyard 923 Passenger Vessel based on the tool analysis. The LNG Constant RPM (LNG-Electric) are the least CO_2 polluting fossil fuel energy carrier.

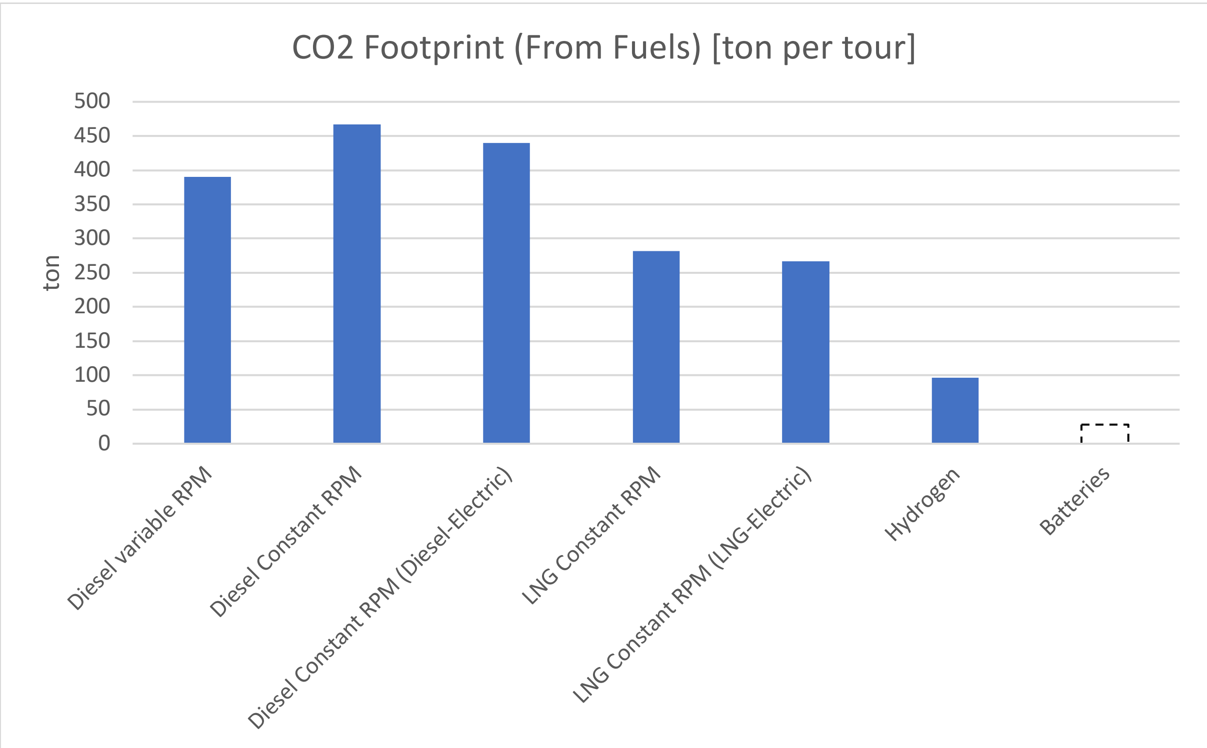


Figure 49 Carbon Footprint from the different powertrains including CO2 emissions and carbon footprint from fuels based on the tool analysis. Design and manufacturing of the engine is no included in these calculations.

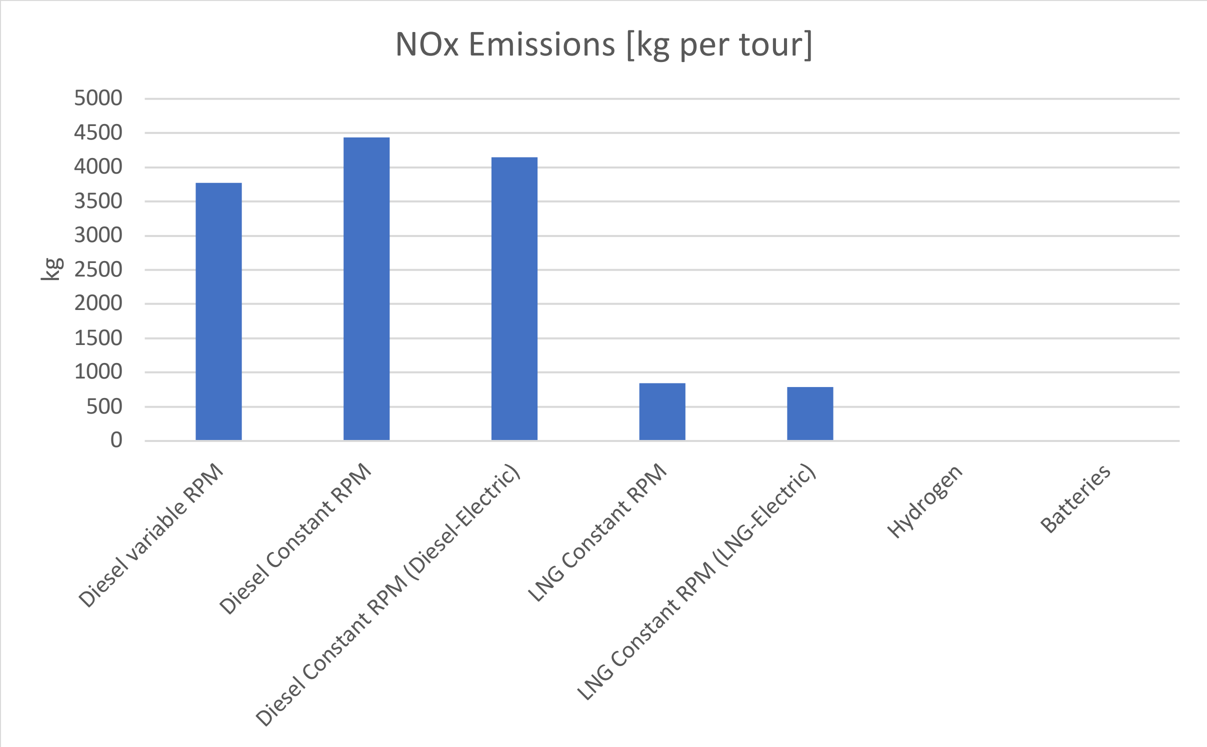


Figure 50 NOx Emissions from the Havyard 923 Passenger Vessel based on the tool analysis. The LNG-engines are polluting less NO_x than the diesel engines, while hydrogen does not pollute any NO_x.

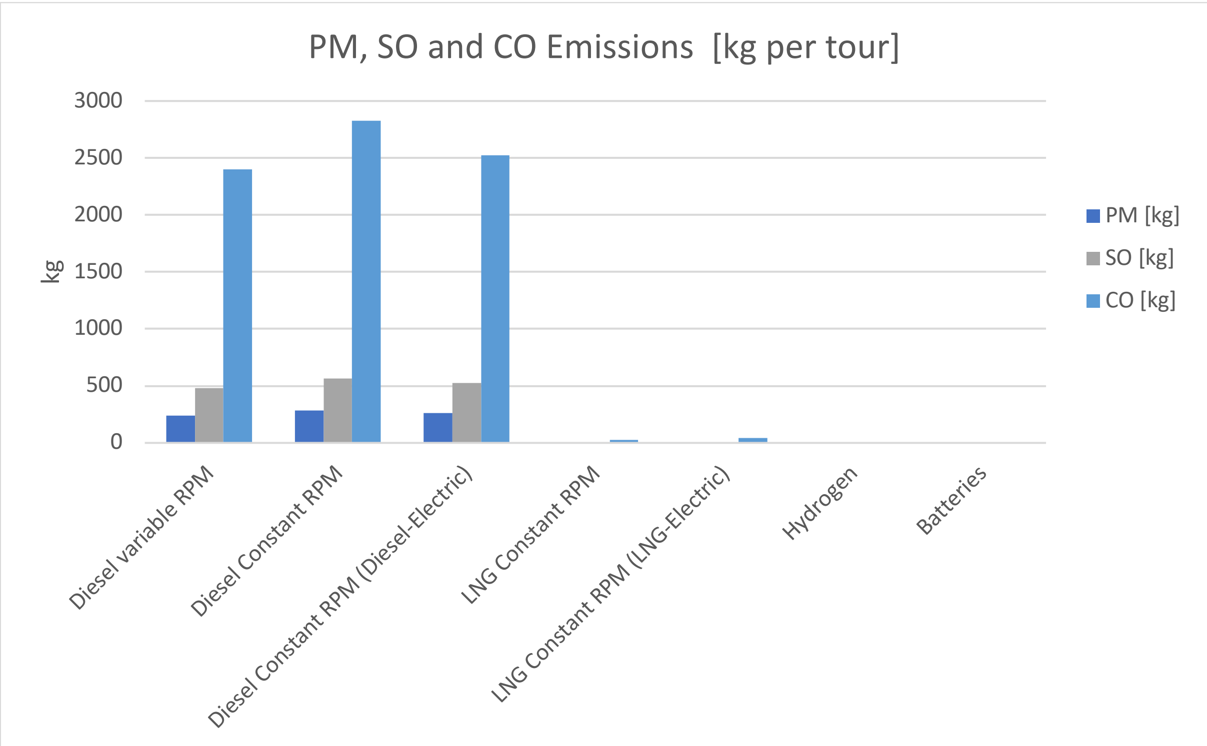


Figure 51 CO-, PM- and SO-emissions from the Havyard 923 Passenger Vessel based on the tool analysis.

4.1.3 Costs

Based on the fuel consumption and the powertrain size of the tool, the twenty-year lifetime costs analysis is shown in Figure 52 and Table 16.

Table 16 Lifetime Cost estimations for the passenger vessel for a 20-year period.

Lifetime Costs estimation							
	Diesel Var.	Diesel const	Diesel-Battery	LNG Const	LNG-Battery	Batteries	Hydrogen
	493	506	627	553	675	1971	39

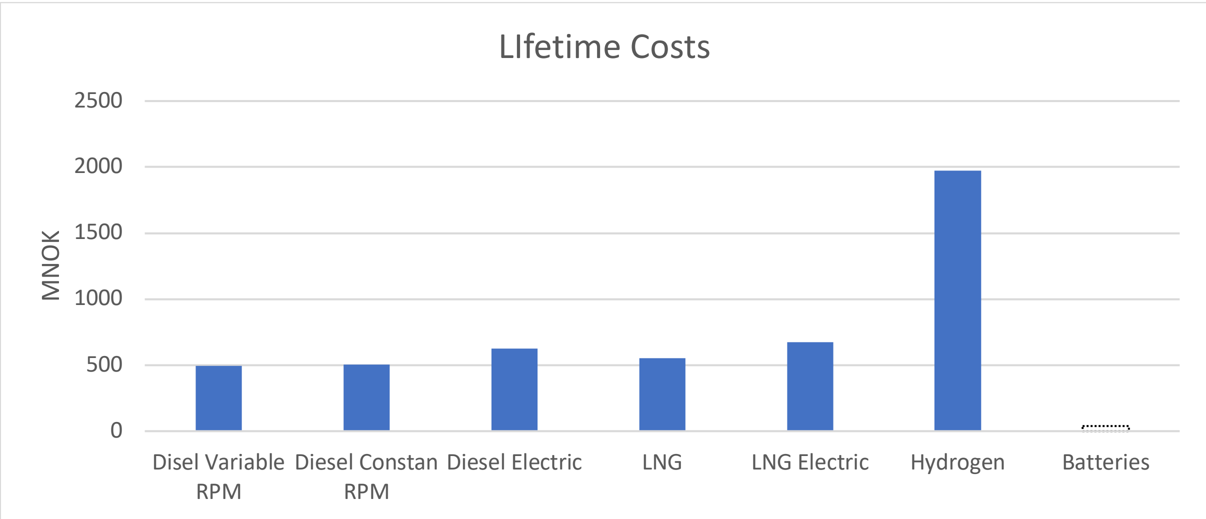


Figure 52 Lifetime Costs estimations for the Havyard 923 Passenger Vessel based on the analysis from the tool. Hydrogen are the least cost-effective energy carrier, while diesel is the most cost-effective energy carrier with the level of cost considered for 2018.

4.2 Double-ended Car ferry

The double-ended car ferry used in this study is a 120 unit car ferry operating between three harbors with shore charging connection.

4.2.1 Energy

Table 17 and Figure 53 shows the representative energy consumption based on engine type for the Havyard 936 120 PBE Car Ferry. As seen, Batteries, Hydrogen and LNG-Hybrid (in that order) are the most efficient powertrains for this study.

Table 17 Energy consumptions for the 120 PBE Car Ferry.

Daily Consumptions					
	Fuel [kg]	Energy, fuel [kWh]	Energy, electricity [kWh]	Used [kWh]	Incl WTWE [kWh]
Diesel variable RPM	2034,0	56757		56757	NA
Diesel Constant RPM	2173,1	59281		59281	NA
Diesel Constant RPM (Diesel-Electric)	1625,1	76376	35460	111836	NA
LNG Constant RPM	1612,5	48135		48135	NA
LNG Constant RPM (LNG-Electric)	1130,2	30571	35460	66031	NA
Hydrogen	359,3	28653	35460	64113	NA
Batteries	0		24341	24341	NA

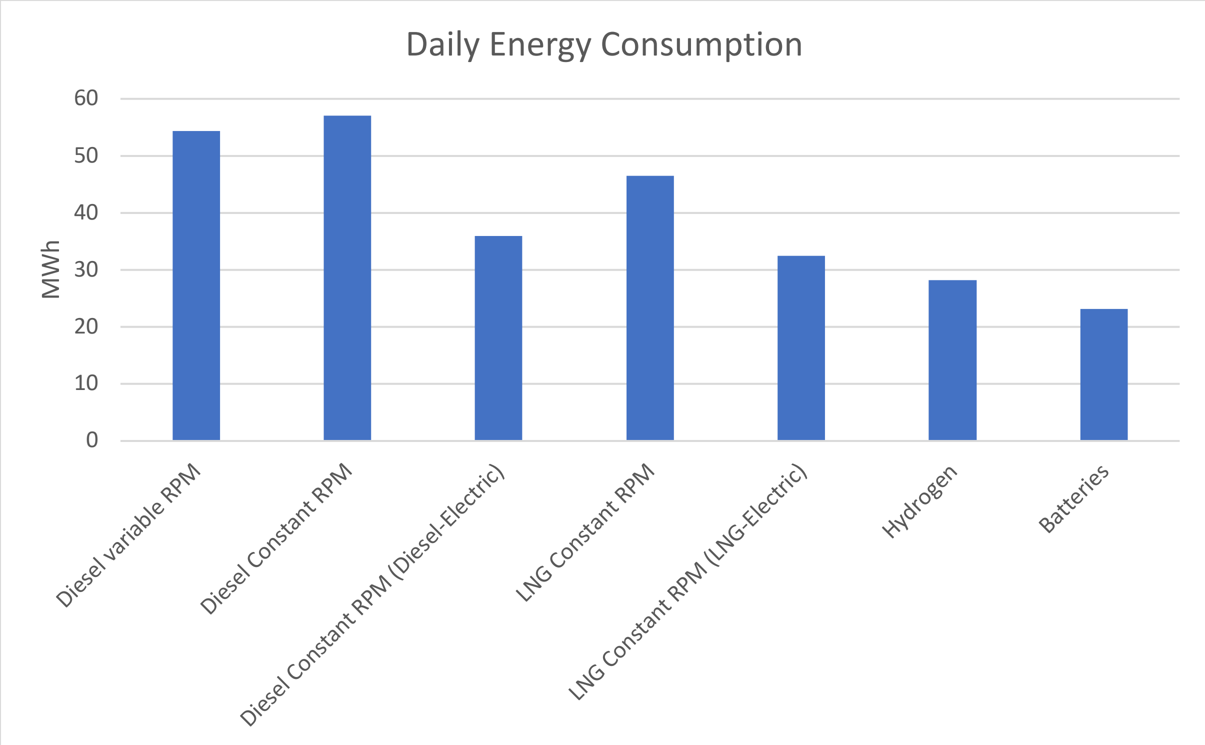


Figure 53 Energy Consumption for the Havyard 936 Double-Ended Car Ferry. The numbers are based on an analysis from the tool. Batteries are the most efficient of the zero-emissions engines.

4.2.2 Emissions

Figure 54 and Table 17 shows the CO_2-emissions from combustion of the fuels for the engine. Diesel-solutions represents the most CO_2 polluting solution, LNG about 25% less than Diesel and no CO_2 is released into air from the combustion of hydrogen usage of batteries.

Figure 55 and Table 17 presents the CO_2 footprint from combustion of fuels and production of fuels. The tool does not consider the footprint from production and maintenance of the different powertrains. When footprint is considered, we can see that Hydrogen and Batteries also has a carbon footprint.

Figure 56 and Table 17 shows the NO_x emissions from the fuels. Diesel is the most polluting one while LNG only pollutes a small percentage of NO_x compared to Diesel powertrains.

Figure 57 and Table 17 represents the other particles and gasses released by burning fuels. Diesel is the most polluting while LNG only represents a smaller part of the same gases.

Table 18 Emissions from the 120 PBE Car Ferry.

Daily emissions							
	CO_2 [kg]	NO_x [g]	CO [g]	PM [g]	SO [g]	Carbon Footprint [t]	
Diesel variable RPM	14940	77818	102678	10268	20536	16	In addition comes the emissions from producing the engine. These are not included in the calculations
Diesel Constant RPM - Hybrid	15609	77818	102678	10268	20536	16	
Diesel Constant RPM (Diesel-Electric)	10693	57819	70972	7097	14194	13	
LNG Constant RPM - Hybrid	10365	31704	1057	106	211	11	
LNG Constant RPM (LNG-Electric)	6086	20353	678	68	136	8	
Hydrogen	0	0	0	0	0	4	
Batteries	0	0	0	0	0	1	

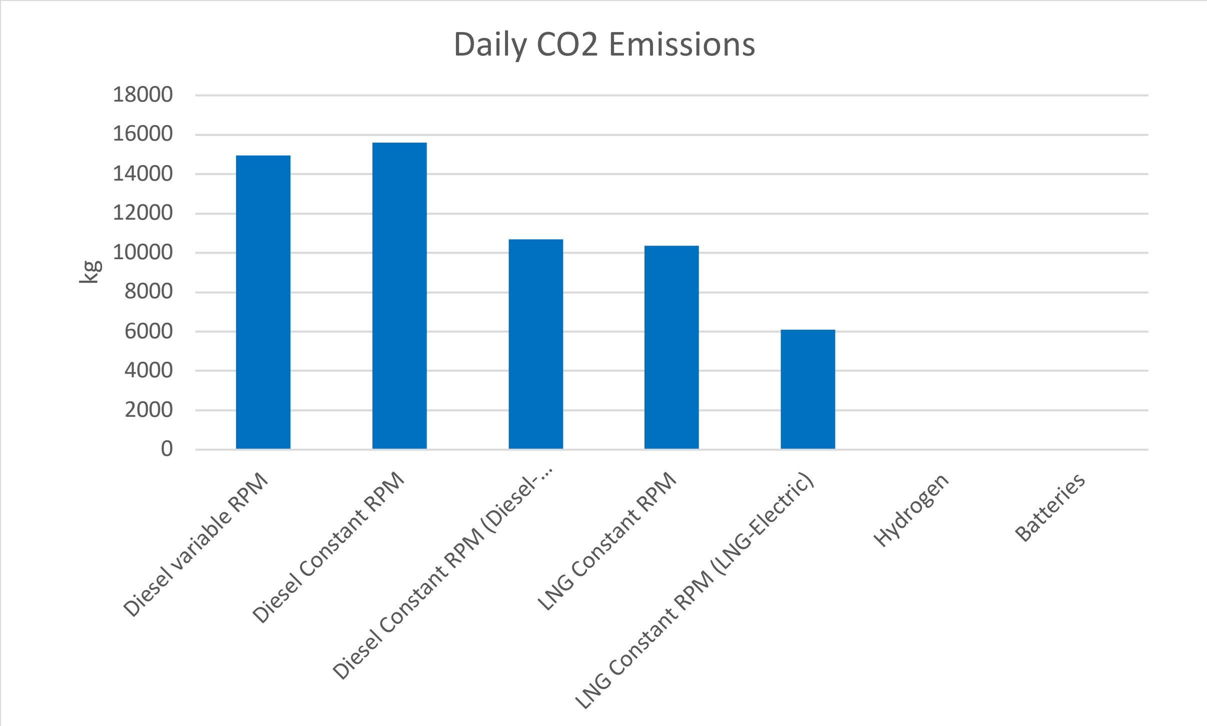


Figure 54 CO_2 emissions in ton per tour for the Havyard 936 Double-Ended Car Ferry on the tool analysis.

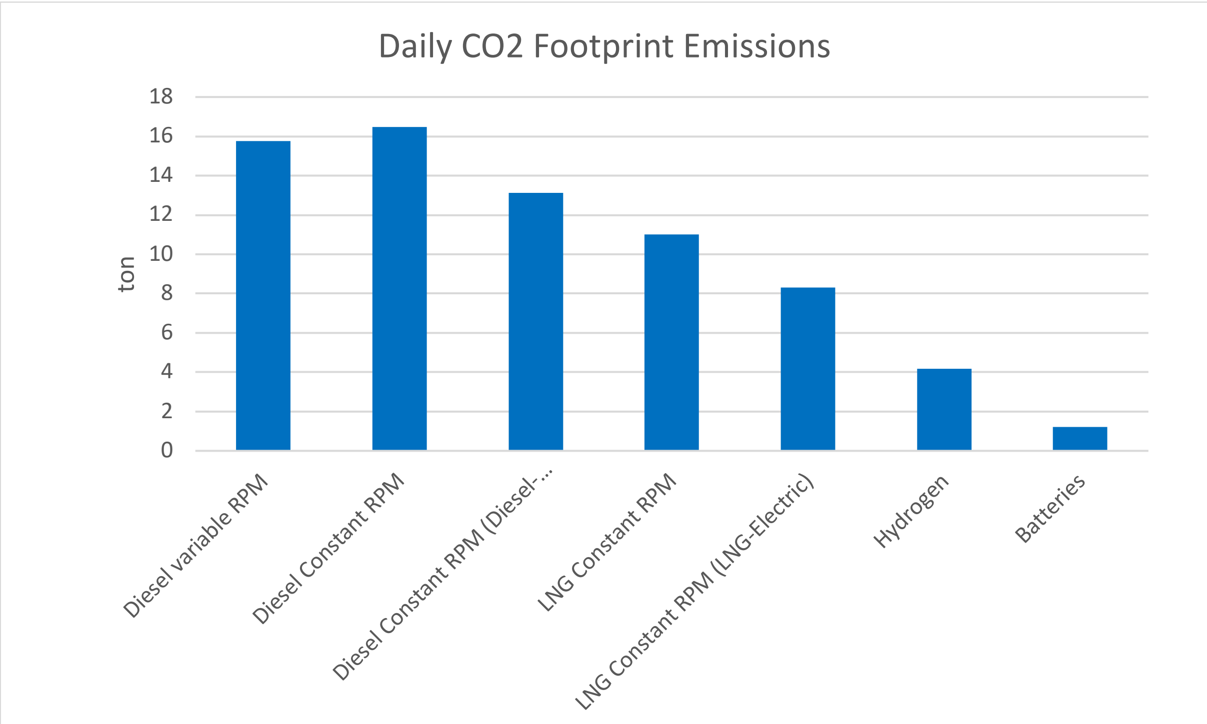


Figure 55 Carbon Footprint from the different powertrains including CO2 emissions and carbon footprint from fuels based on the tool analysis.

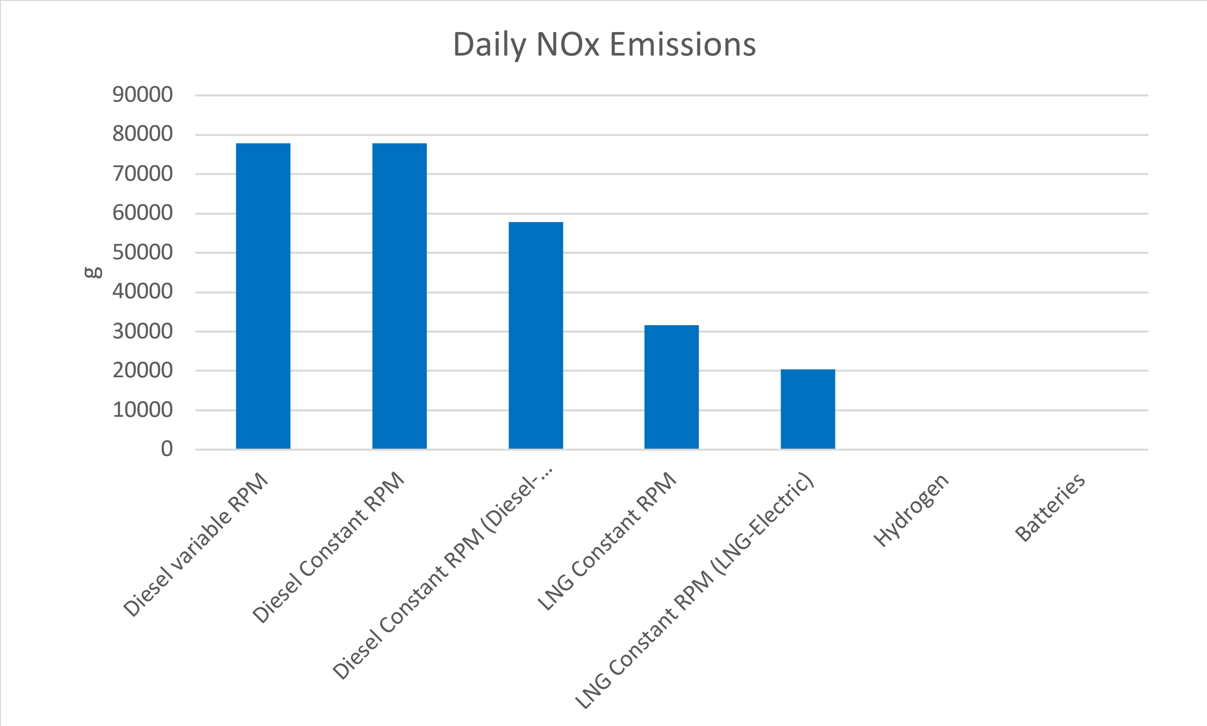


Figure 56 NOx Emissions from the Havyard 936 Double-Ended Car Ferry based on the tool analysis.

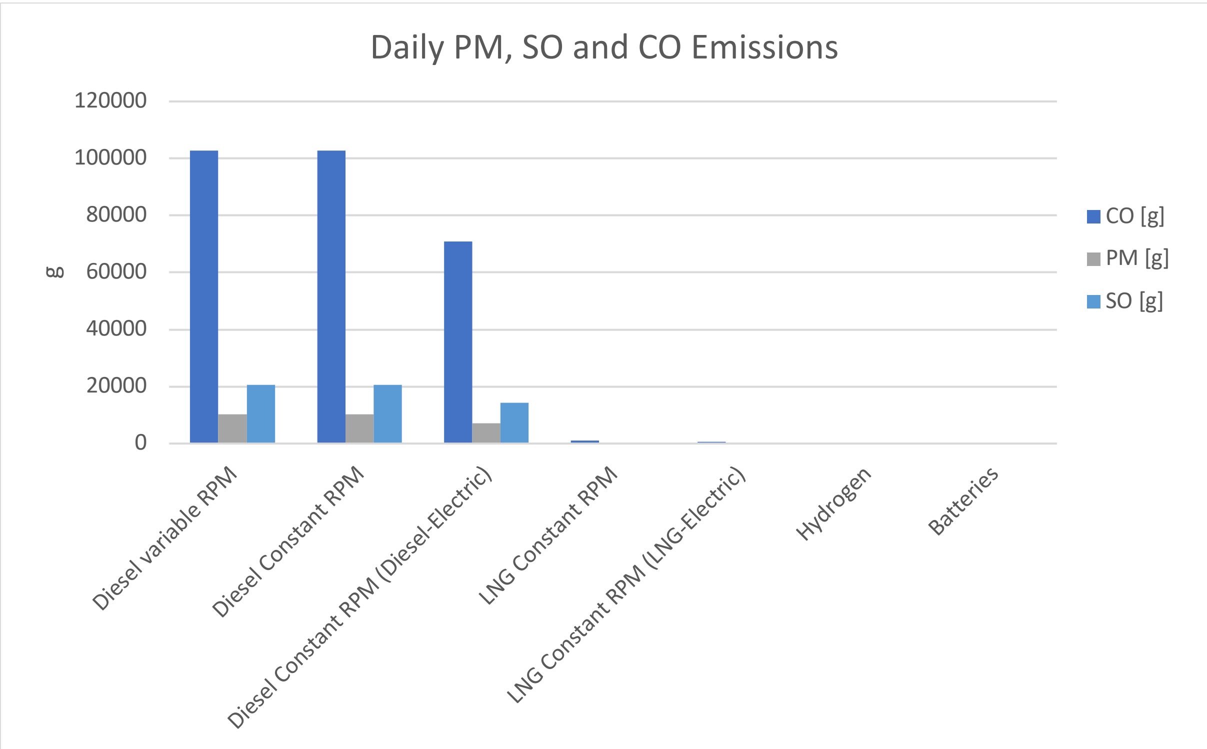


Figure 57 CO-, PM- and SO-emissions from the Havyard 936 Double-Ended Car Ferry based on the tool analysis. The emissions are dramatically reduced by use of LNG-engines and avoided by use of hydrogen and batteries.

4.2.3 Costs

Based on the fuel consumption and the powertrain size of the tool, the twenty-year lifetime costs analysis is shown in Figure 58 and Table 19.

Table 19 Life Time Cost Estimations for the 120 PBE Car ferry

Lifetime Costs estimation							
Diesel Var.	Diesel const	Diesel-Battery	LNG Const		LNG-Battery	Batteries	Hydrogen
135	141	189	134		183	430	80

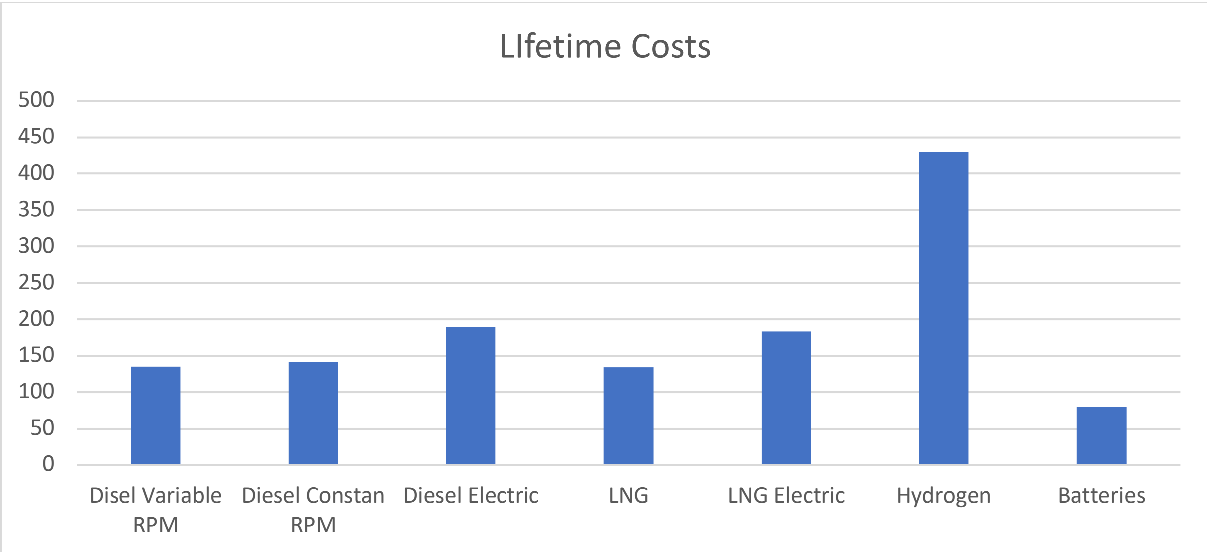


Figure 58 Lifetime Costs estimations for the Havyard 936 Double-Ended Car Ferry based on the analysis from the tool.

4.3 Live fish carrier

The live fish carrier studied in this master´s thesis is based on a Havyard 587 design shown in Figure 59. Since all performance data estimated from Havyard is confidential information, the values used in the tool estimation are only suggested values based on the study trip onboard Steigen. If the tool is working properly, the values from NFT Steigen and the estimated calculations in the tool should be almost similar.

Figure 59 The Live Fish Carrier NFT Steigen. Photo: Jørgen Kopperstad.

The first results will present the energy consumption, the emissions and the costs for the Havyard 587 based on the analysis. The settings used for the live fish carrier are based on interviews of the crew onboard NFT Steigen. All settings can be found in appendix C. One important setting is that it is assumed that 15% of the energy through one day comes from batteries onboard the ship which means that a 8608 kWh battery is needed.

4.3.1 Energy

Figure 60 and Table 20 shows the representative energy consumption based on engine type for the Havyard 587 Live Fish Carrier. As seen, Hydrogen and LNG-Hybrid (in that order) are the most efficient powertrains. Based on the results from the tool, batteries are considered less favorable for this ship type. This is mainly due to charging time, weight of batteries and the operation of the ship.

Table 20 The daily consumptions for the Live Fish Carrier.

	Daily Consumptions				
	Fuel [kg]	Energy, fuel [kWh]	Energy, electricity [kWh]	Used [kWh]	Incl WTWE [kWh]
Diesel variable RPM	11257	135		135	NA
Diesel Constant RPM	11442	137		137	NA
Diesel Constant RPM (Diesel-Electric)	10924	131	9	140	NA
LNG Constant RPM	8563	117		117	NA
LNG Constant RPM (LNG-Electric)	8569	103	9	111	NA
Hydrogen	2527	100		100	NA
Batteries	NA	NA	54	54	NA

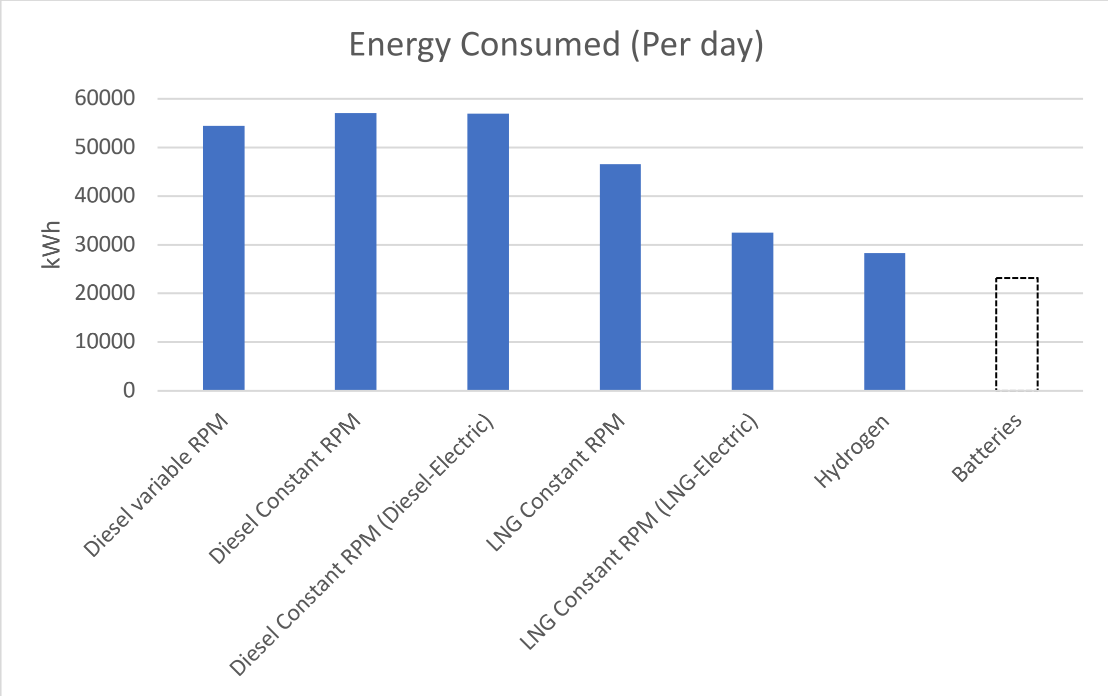


Figure 60 Energy usage for the Havyard 587 Live Fish Carrier based on the tool. Hydrogen is the most efficient powertrain if batteries are not considered.

4.3.2 Emissions

Figure 61 and Table 21 shows the CO_2-emissions from combustion of the fuels for the engine. Diesel-solutions represents the most CO_2 polluting solution, LNG about 25% less than Diesel and no CO_2 is released into air from the combustion of hydrogen usage of batteries.

Figure 62 and Table 21 presents the CO_2 footprint from combustion of fuels and production of fuels. The tool does not consider the footprint from production and maintenance of the different powertrains. When footprint is considered, we can see that Hydrogen and Batteries also has a carbon footprint.

Figure 63 and Table 21 shows the NO_x emissions from the fuels. Diesel is the most polluting one while LNG only pollutes a small percentage of NO_x compared to Diesel powertrains.

Figure 64 and Table 21 represents the other particles and gasses released by burning fuels. Diesel is the most polluting while LNG only represents a smaller part of the same gases.

Table 21 Daily emissions from the live fish carrier studied in the tool.

Daily emissions							
	CO_2 [kg]	NO_x [kg]	PM [kg]	SO [kg]	CO [kg]	Carbon Footprint [t]	
Diesel variable RPM	35684	388	25	11	247	40	In addition comes the emissions from producing the engine. These are not included in the calculations
Diesel Constant RPM	36272	381	24	11	243	41	
Diesel Constant RPM (Diesel-Electric)	34629	366	23	11	233	39	
LNG Constant RPM	23600	82	0	0	3	27	
LNG Constant RPM (LNG-Electric)	23616	70	0	0	2	28	
Hydrogen	NA	NA	NA	NA	NA	8	
Batteries	NA	NA	NA	NA	NA	3	

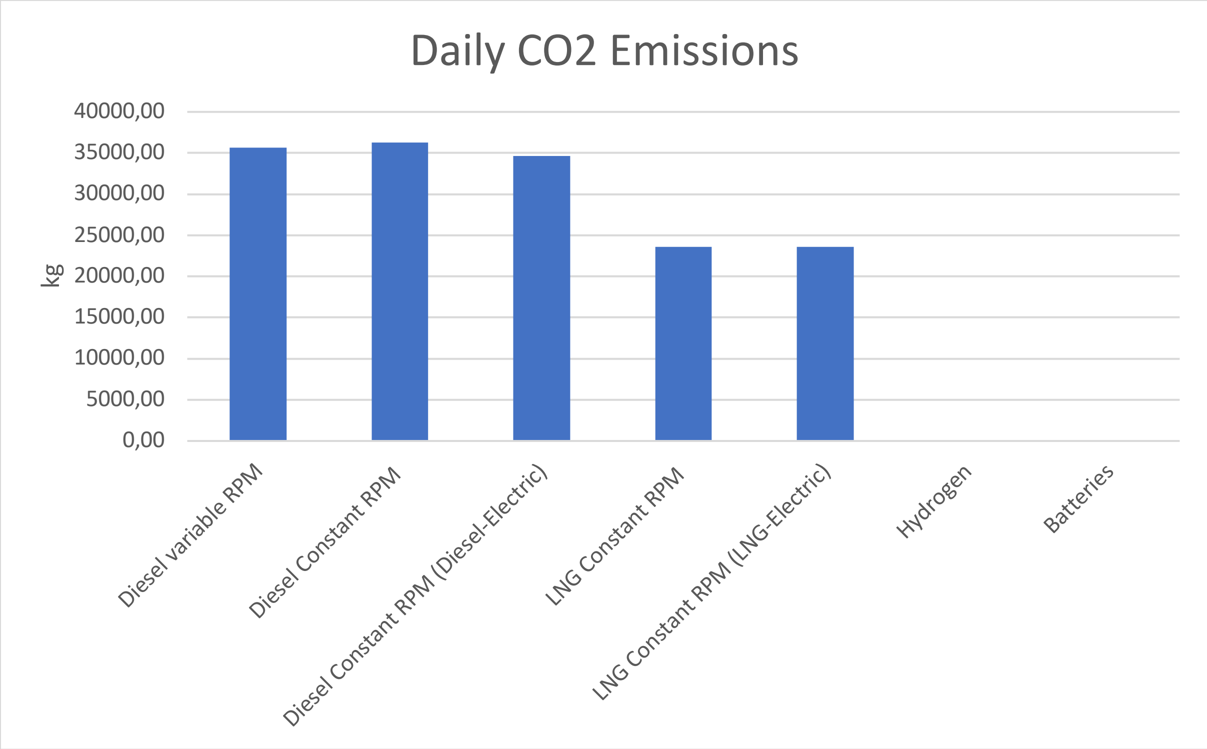


Figure 61 CO_2 emissions in ton per tour for the Havyard 587 Live Fish Carrier based on the tool analysis.

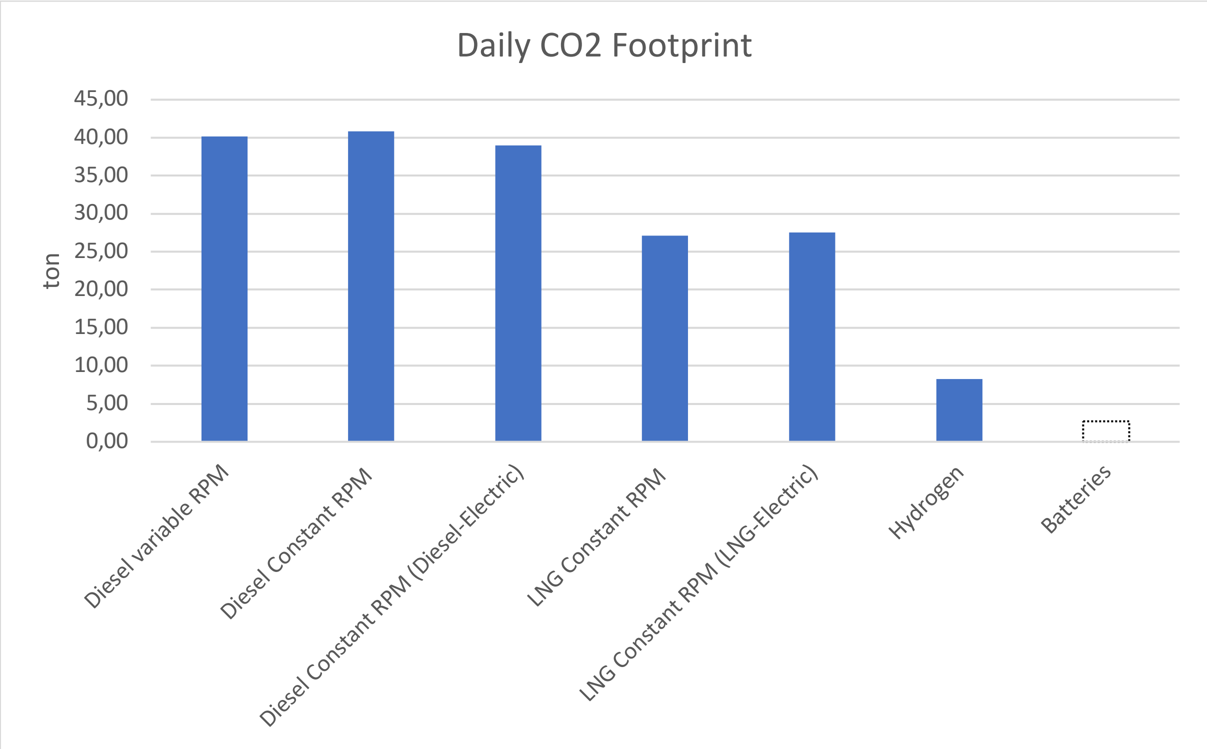


Figure 62 Carbon Footprint from the different powertrains including CO2 emissions and carbon footprint from fuels based on the tool analysis.

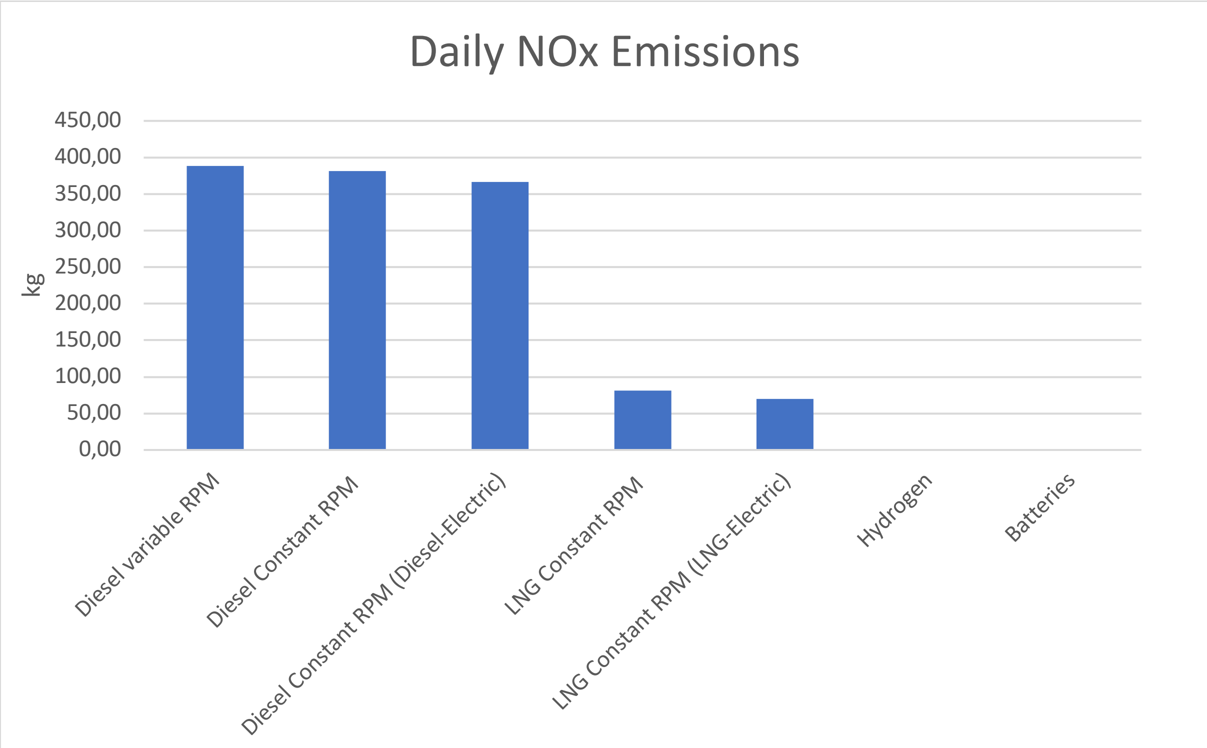


Figure 63 NOx Emissions from the Havyard 587 Live Fish Carrier based on the tool analysis.

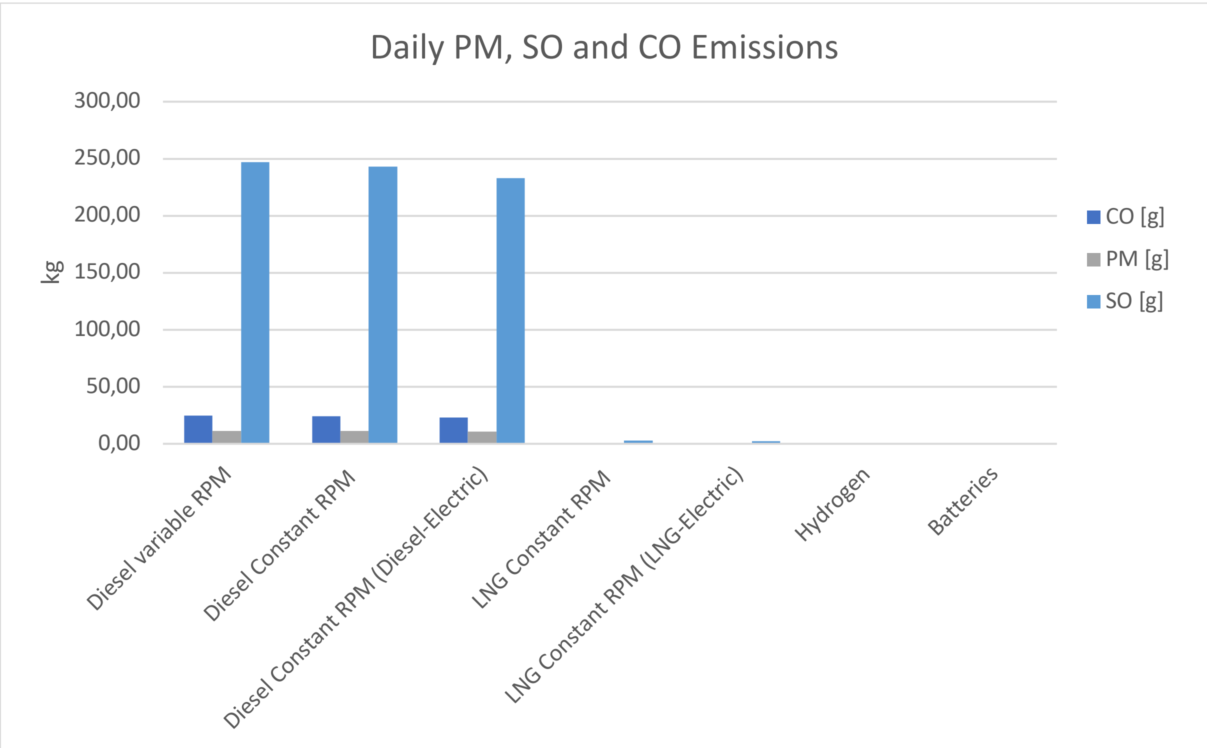


Figure 64 CO-, PM- and SO-emissions from the Havyard 587 Live Fish Carrier based on the tool analysis.

4.3.3 Costs

Based on the fuel consumption and the powertrain size of the tool, the twenty-year lifetime costs analysis is shown in Figure 65 and Table 22.

Table 22 Life Time Cost estimations for the Live Fish Carrier.

Lifetime Costs estimation						
Diesel Var.	Diesel const	Diesel-Battery	LNG Const	LNG-Battery	Batteries	Hydrogen
314	319	399	303	361	1116	555

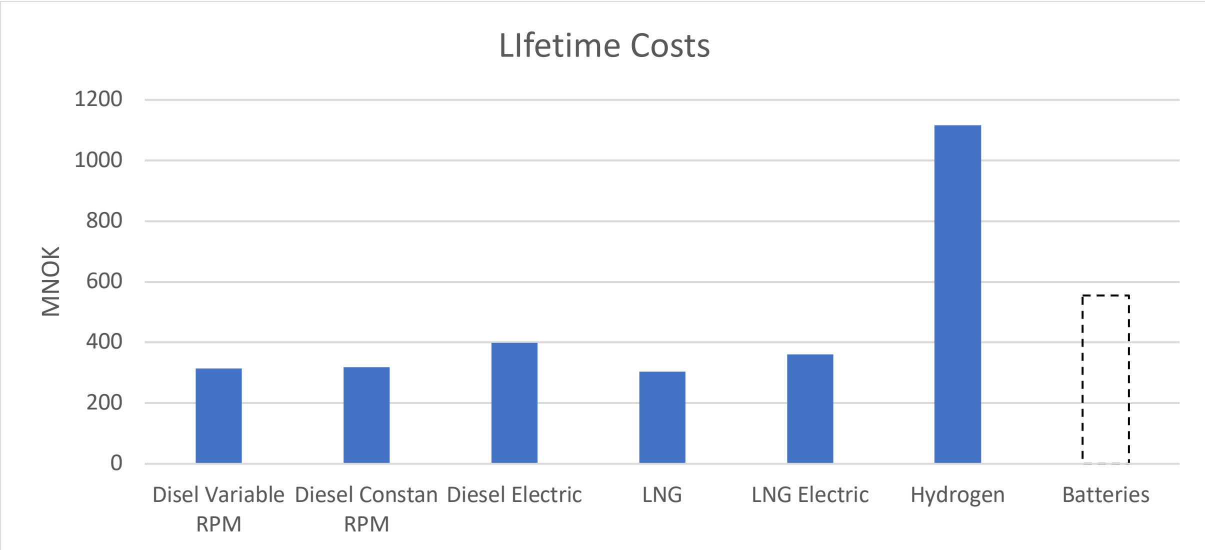


Figure 65 Lifetime Costs estimations for the Havyard 587 Live fish Carrier based on the analysis from the tool.

4.4 Study Trip

On the study trip to Steigen, one of the most valuable results were the in-operation monitoring of the Power-Speed curve. The reference power for the admiralty curve is 3000 kW at 13,7 knots. This can be used for evaluating the correctness of the admiralty curve for this design. Figure 66 shows the compared admiralty curve vs the power-speed curve monitored onboard.

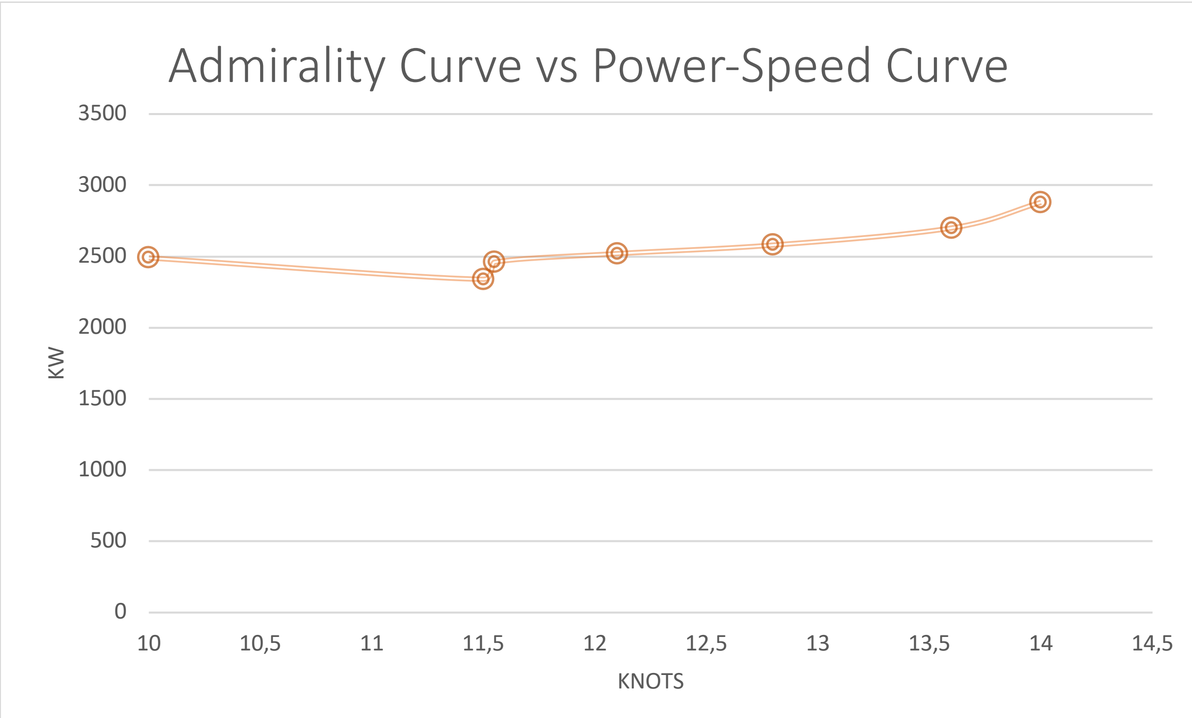


Figure 66 Power-Speed Curve for NFT Steigen (orange line) vs the admiralty curve (Blue line). The measurements were made in Vestfjorden in Norway without precise logging of currents and wind. The measured power is the overall power (both hotel and propulsion). There were no fish or water in the tanks during these tests, and only about 300 kW of the measured energy were used for other purposes than propulsion.

4.4.1 Observations

In the following subsections several observations done onboard NFT Steigen will be presented.

4.4.1.1 Harbor generator

A longer period of the study trip was spent in harbor in Bodø. In February the temperatures are low and therefore additional heating is necessary onboard. A harbor generator is placed onboard to supply the ship with energy while in harbor.

The harbor generator is at 250 kW and is designed to supply sufficient energy to run the system while in harbor. There are also two generator sets at 1000 kW each in addition to the main engine at 3000 kW.

Some months before the student visit NFT Steigen the crew realized that there was not sufficient heating onboard to avoid freezing in pipes in outside the isolated superstructure. Therefore, heating fans were bought and placed around the ship. Because of this, the average consumption of NFT Steigen in harbor in Bodø in February were around 300 kW, this meaning that one of the two generator sets onboard had to be started.

4.4.1.2 Fish handling

While the student was onboard NFT Steigen, he had the chance to observe three different operators running the fish handling system from the bridge. All three of them ran the fish handling system in different ways with different energy consumptions, variating with as much as 10% in energy demand.

5. Discussion

In this section, the approach in the tool and the results are discussed.

5.1 Functionality of the tool

Since the beginning of the project the main focus has been on developing a tool or a method that is simple to use and does not demand further knowledge in any of the four disciplines studied.

The simple version of the tool is very simple. Only a few inputs are necessary to fill in for someone who does not have the opportunity to fill in more values or for someone who only need a very rough estimate for the analysis. The most challenging simple input version is the one for the live fish carrier, where a design route is necessary to be able to say something about batteries. This feature is anyhow very useful, because it can be used to explain why battery technology can be difficult to use for live fish carriers. By opening a second window for the tool and having sheet B1 and F open at the same time, the necessary charging, battery size and weight can be monitored while the design route is being modified.

If only simple inputs are used, there are anyhow varieties in how representative the result you get is. There are an unlimited number of alternatives for a ship design and by using simple inputs, you only consider a small range of opportunities.

When modifying the advanced inputs there is a wide range of opportunities to achieve a more precise result, for example through editing the ship resistance curve, load-curves for engines, losses, costs and margins. The useful about advanced inputs, is that there are actually no limitations for what you can implement if you have an average high level of knowledge in ship design.

Several important factors that are expected to change in years to come can be covered by modifying the advanced inputs. These include e.g.:

- Expected development in fuel prices
- CO_2 tax development
- Carbon footprint from installation of engines
- Costs of other engine dependent components onboard the ship such as fuel tanks, transformers and etc.
- Heat-recovery systems
- Many others

Because of the complexity of the tool, the focus has been on developing a simple version with a proper methodology with opportunities for improvements. The tool is working properly, but more add-ins are necessary to give representative results for the simple version or even for the advanced version if it is supposed to be used as it is. The numerical accuracy of the tool can also be improved.

An example of a work-through for the missing functions mentioned above is that for example the heat-recovery system can be included by adding the efficiency obtained by heat-recovery by adding it to the engine curve. The carbon footprint of production of engines can also be added by finding the footprint per kW installed capacity and hence adding it to the footprint.

5.2 Preciseness of answers

It was difficult to verify the results from the tool. One of the objectives with the study trip onboard Steigen were to collect data for fuel consumption. Onboard the Live Fish Carrier the student found out that the fuel-meter didn´t work properly and that the load curves were difficult to read from the graphical user interface on the bridge.

An attempt was made to collect data from ship owners running any of the ship types studied without success. In general, fuel consumptions and costs of operation are sensitive information used in the competition between the different suppliers.

The admiralty curve is one of the simplifications made that can lead to a less precise answer if used. Figure 66 shows the comparison between the admiralty curve for the live fish carrier based on a given design speed and design speed power compared to power-speed data logged during testing. The comparison shows that the actual power consumed at 10 knots is about 110% more than the admiralty curve suggests. There can be several reasons for this, but the differences in power-speed for the actual ship compared to the admiralty coefficient is one of the uncertainties that can explain this.

It is difficult to say something about the actual effect of hybridization without testing it onboard a ship. Hybridization can improve the performance through several ways, amongst other through peak shaving and by possibly reducing the main engine size. In the tool, reduced engine size and charging from shore are calculated. Improved performance through peak shaving is not included. There are big uncertainties when it comes to defining the real effect of having batteries onboard.

The best way of discussing the preciseness of the tool is by comparing it with the expected results. It is expected that diesel engines emit more than any of the other systems, which the tool confirms. It is also expected that LNG emit less than diesel, but far more than hydrogen and battery systems if carbon footprint from fuels are not considered. If carbon footprint is considered, the difference is lower.

Based on the expected result of the tool, there are no reason to deny the results calculated for emissions and consumptions.

It is necessary to improve the life-cost-analysis part of the tool before the outcome will be more than just for indicative purposes. The results presenting lifetime costs, capex and opex are anyhow very useful for learning more about where the costly factors are making non-fossil fuels more difficult to introduce. An example for this is that it is easy to see that replacing fuel cell stacks every third or fourth year represent a significant post in the budget. Reducing the cost or increasing the lifetime will most likely make hydrogen a more interesting solution for shipping in the future.

5.3 Results

This section will be a discussion of the different results found by use of the tool.

5.3.1 Live Fish Carrier

The Live Fish Carrier analysis was a bit more complex than the others since this vessel isn´t operating a consistent route but is doing different operations through a year.

The results found for the Live Fish Carrier can be seen as a result verifying the effect of the tool. NFT Steigen is today operating with a diesel mechanic propulsion system with a constant rpm engine using variable propeller pitch to increase or decrease the speed and additional generators to provide the peak energy demands during operation. The fact that the tool provided results presenting diesel constant rpm as the most efficient propulsion system and with the least pollution among the diesel systems is probably the same results the designer found when the ship was designed.

Diesel variable rpm has almost the same life time cost estimation as diesel constant rpm (Diesel variable RPM is estimated to cost 365 MNOK through 20 years and Diesel Constant RPM is estimated to cost 366 MNOK). Since it is easier to combine a constant rpm engine with a generator to provide electricity, this is probably the reason why constant rpm were chosen as the setup for the main engine.

Onboard Steigen the officer on the bridge and the chief engineer also demonstrated running the ship´s engine with variable rpm. Then the necessary electricity was provided by starting one of the two generators at 1000 kW. The main engine was disconnected from the shaft generator. This resulted in a small increase in fuel consumption.

The results found for the Live Fish Carrier was considered representative compared to each other, but due to the missing details of engine setup there are differences between results shown and the performance for the ship. According to the crew onboard, there are often many other factors than only consumptions and costs that are considered during operation. Factors such as fish care, speed of operation, areas available for medical treatment of the fish and human touch are factors that will have to be included to find a precise result. Some of these factors may be difficult to include in a numerical analysis.

Engine setup are also different from the setup in the tool. While the tool considers a ship with one fossil fuel engine, NFT Steigen has *one* engine, *two* additional generator sets and *one* harbor generator. There are thousands of different engine setups available for each ship design and undefinable factors such as human touch and special needs can affect the engine setup. If the tool were designed to analyze only this specific design, it would be useful to provide specific fuel consumptions and load curves representing the different operational modes and which engines that are running and at which load.

NFT Steigen rarely uses shore connection and has no system for heat recovery. Therefore, the fact that these add-ins are missing in the tool does not affect the result of the calculation. It would anyhow had been interesting to see what effect such installations would have on the performance.

Using batteries for a live fish carrier is difficult. If a customer needs a ship to operate in a limited area with limited range, batteries can be an alternative to achieve zero emission systems, if the costs of batteries are reduced. The tool has provided a “Design-operation” where the size of the battery necessary to make the ship capable of doing this specific operation is calculated. Hydrogen is easier to use, since it doesn´t represent the same limitation in range as for batteries and since the charging/fueling time is shorter. Anyhow, hydrogen represent a lifetime cost 3,6 times higher than for the diesel constant rpm alternative. Changing from for example diesel to hydrogen represents a carbon footprint reduction of 13 000-ton CO_2 per year (installation and production cost of the engine is not included in this estimate). The hydrogen solution is also more efficient than the diesel engine option used.

5.3.2 Passenger Vessel

There are no data available data to compare the results found with the ships currently in operation. It is therefore difficult to verify or deny the results found in the calculations. The relative outcomes do anyhow represent a likely difference between the different fuels.

For fossil fuels, LNG is the most efficient fuel. If renewables are included, batteries consume only 46% of the energy used by a similar setup with LNG-hybrid alternative. The batteries are anyhow very expensive and are most like not possible to use due to weight and capacity. In the setup considered in the tool due to charging capacity.

Hydrogen is possible to use and more efficient than LNG-engines. The challenge for hydrogen powered powertrains is anyhow the cost of fuel cells and hydrogen.

It is known that Havyard Design & Solutions has designed their new passenger vessel design with a LNG-electric powertrain to achieve the strict CO_2-limits given by the contractor. The tool verifies that LNG-hybrid is the fossil fuel powertrain with the smallest CO_2 emissions and with a competitive level of costs.

5.3.3 Double-Ended Car Ferry

For the Double-Ended Car Ferry analysis, it is easier to study the operation since it is repeatable. In this study, it is assumed that the available shore power is 4000 kW and therefore the hybrid solutions are assumed partly powered by batteries. A simplification is made assuming that all in and out of harbor operations are powered only by the fossil fuel engines. This is a rough estimation that should be considered improved.

The results present in this case is the same as in the two others; diesel-engines pollute more than LNG-engines and among the zero-emissions solutions, hydrogen is the most expensive. Since batteries are possible to use for this route and the emissions, the footprint and the costs for batteries are the lowest, it would have been recommended to use batteries for this design. For most short-distance fjord crossings assigned new contracts with new operators the last year, battery ferries have been agreed upon.

The studied ferry connection is a relative short connection. Some connections like for example Halhjem-Sandvikvåk is longer. By use of the tool, it can be shown that to sail the 11,7 nautical miles this ferry has to operate, it will need a 3671-kWh battery. It will also need 23,5 minutes in port for charging if there is 4000 kW of charging capacity. It will still be cost competitive with the other engines. This is shown in Figure 67. It is anyhow big uncertainties that can make the other systems more preferable. To be able to charge with an effect of 4000 kW at each side of the crossing, it will most likely have to be invested in the power grid. The connection is also very exposed.

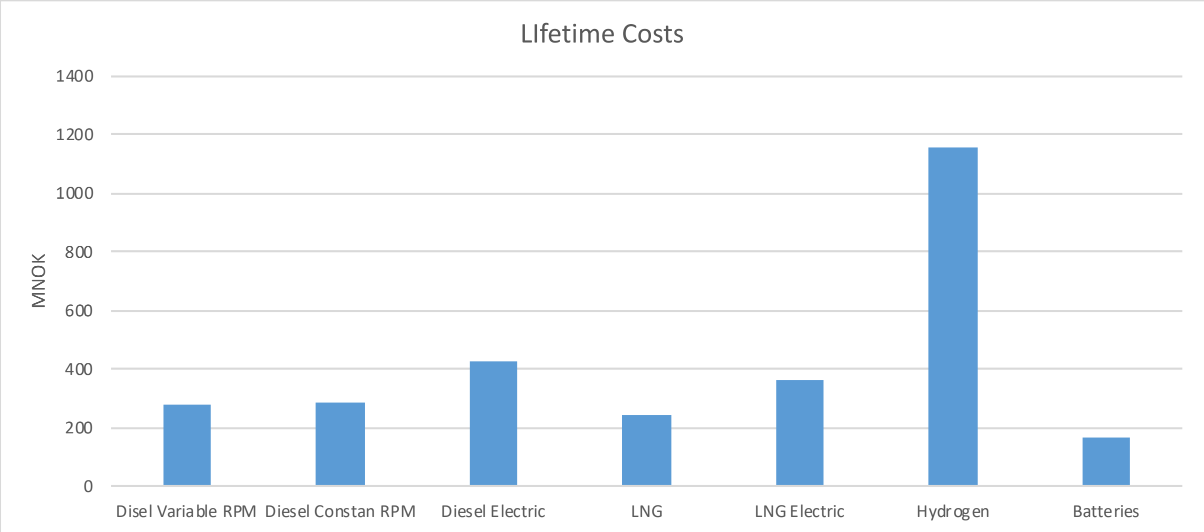


Figure 67 A Life Cost Estimation for Halhjem Sandvikvåg. Batteries are still more cost effective than the other systems if land infrastructure are not considered.

But what if fuel cell lifetime is improved, costs of hydrogen are reduced, and the cost of fuel cells also are reduced? This were calculated, and the result are shown in Figure 68. The ferry connection in Figure 68 also has a 1500 kWh battery package onboard that are charged when in port. The available charging capacity in port is kept at 1400.

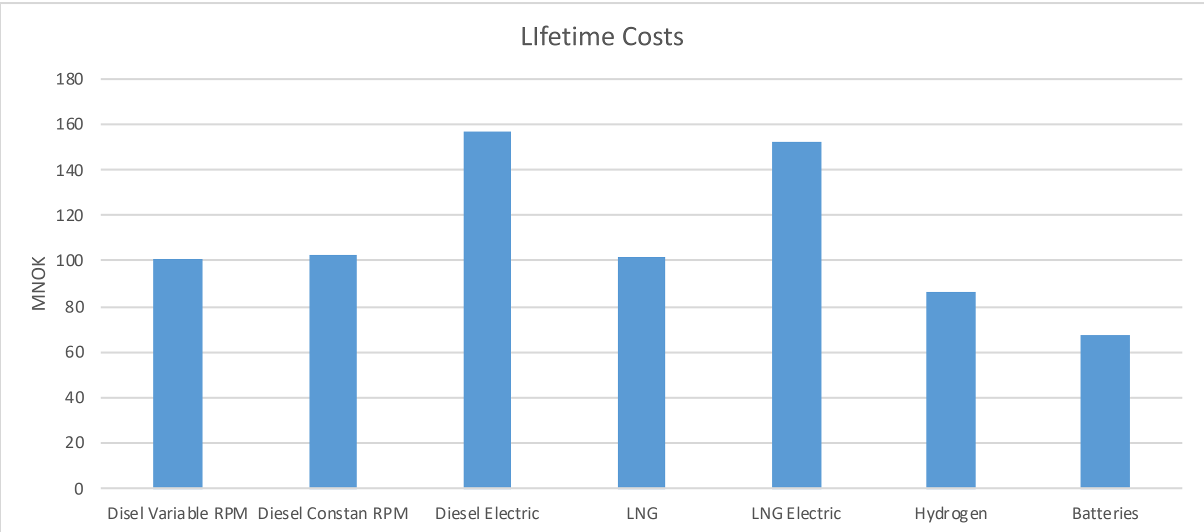


Figure 68 Lifetime costs if fuel cell lifetime is improved to 80 000 hours, cost of hydrogen is reduced to 0,253 kr/kWh and cost of installation are reduced to 400 kr/kW.

The result in Figure 68 can indicate that in the future, a hybrid energy system with fuel cells and batteries may be the answer. Even though the hydrogen system has a higher lifetime cost than for batteries, the time in port, available charging and flexibility of the ship is better for the hydrogen solution.

5.4 Critical values with high uncertainties

Some of the predefined values have a critical impact on the final result, and some of them are variables given with high uncertainties. Some of the most uncertain values are the cost-related multiplication factors such as expected installation cost, fuel cost and lifetime. For example, are fuel cells estimated to cost approximately 13 000 kr/kW. In the future it is suggested by some that the cost of fuel cells can be as low as 400 kr/kW. [55] The available hydrogen fuel cost is now at 2,28 kr/kWh. Some producers claim to be able to sell hydrogen in a few years for 0,253 kr/kWh (non-renewable). The development of these factors will affect the result dramatically.

For engines the most critical value is the load-dependent performance curve. There are a wide range of engines buyable at the market with different efficiencies. For mega-tankers sailing across oceans the engines often are more efficient than the ones used in this tool, mainly because of the size of the engine.

Route studies use sea margin to estimate the added resistance due to weather. This is a very rough estimation mainly based on the average expected resistance. It can be more or less than the resistance used to calculate the energy consumption. It is useful to meet up with the customer before the ship is built and agree upon a sea margin used for calculations.

For ships operating various routes such as live fish carriers, the route study model used in this tool also brings uncertainties. The route can vary a lot and therefore the energy consumption used for calculations in the design phase of the ship can be very different from the actual route operated for the ship when in production. It is therefore recommended that the designer of the ship agrees upon a design route in agreement with the customer.

5.5 Possibilities for transition from fossil fuels to renewable energy

In this section the student will discuss possible transitions from fossil fuels to renewable energy.

5.5.1 Hydrogen

Hydrogen powertrains represents a possibility for a transition from fossil fuel engines to renewable fuel technology. Still, there are few vessels operating on hydrogen and most of them are doing so for research purposes.

In October 2017 the student visited Toshiba R&D center and the Tokyo University of Marine Science and Technology in Tokyo, Japan. The two parties are working together in developing fuel cells. A 50-kW (Figure 70) fuel cell module is mounted onboard a boat (Figure 69) to log efficiency, temperature and other useful data for future developments. According to Technical Adviser Toshio Shimizu in Toshiba their goal is to design an electricity-hydrogen-electricity system with an overall efficiency of 80% and an estimated lifetime of 85 000-90 000 hours.

Figure 69 Hydrogen Powered hybrid vessel owned by Tokyo University of Marine Science and Technology.

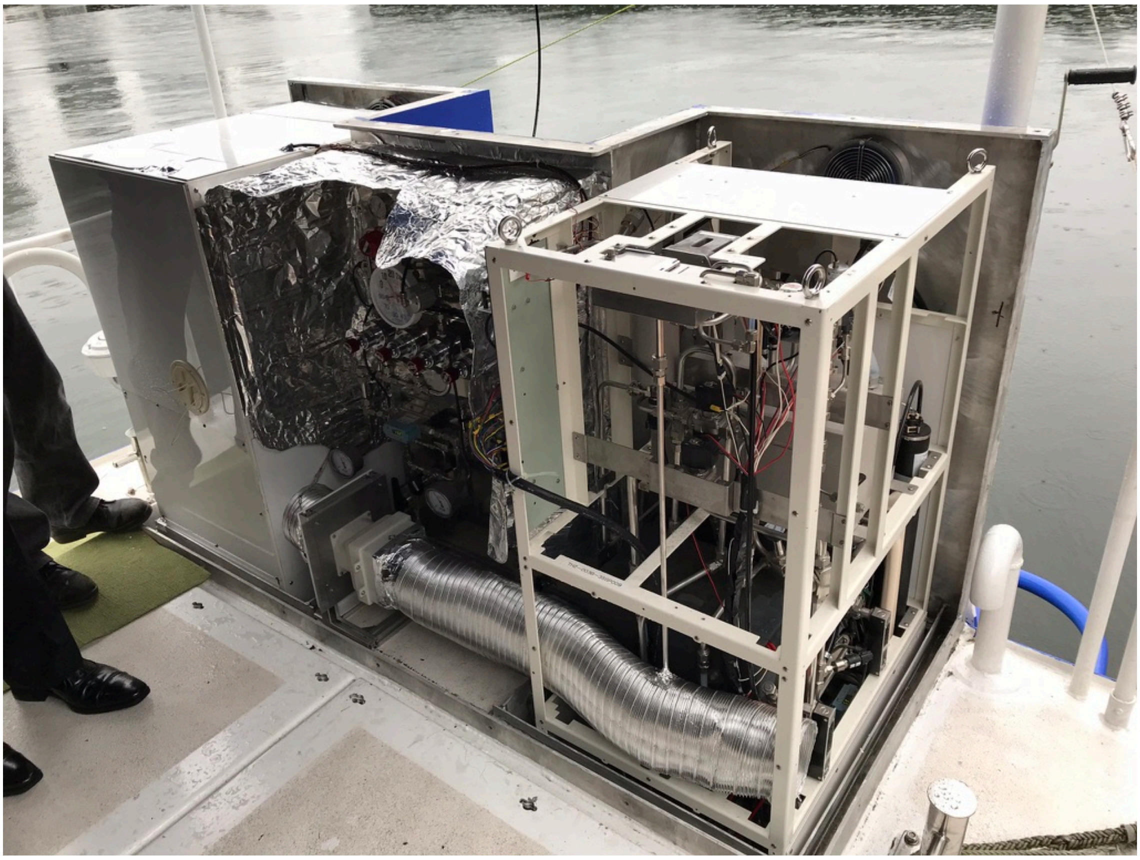


Figure 70 Fuel-Cell Stack onboard the research vessel. The fuel Cells are produced by Toshiba.

The US Department of Energy predicts that if a mass production of approximately 500 000 units per year at 80 kW becomes a reality, the price of fuel cells can drop to a price as low as $50/kW (or approx. 400 NOK/kW based on conversion rate) [55]. The price of hydrogen is also rapidly discussed. Torkild R. Reinertsen from the oil service company Reinertsen has stated that their plan is to produce hydrogen from natural gas (this is not zero-emission production of hydrogen unless carbon capture and storage is used) with a price of about 10 NOK/kg (or 0,253 NOK/kWh).

Figure 71 presents the costs if all cost reductions above becomes a reality for the Passenger Vessel analyzed. Lifetime is improved, cost of fuel cells is reduced, and fuel costs are lowered. The difference can be even bigger if it assumed that carbon tax for LNG and Diesel is increased. Figure 71 also doesn´t include improved efficiency for fuel cells. If 80% efficiency is improved, it is expected that the fuel costs will half.

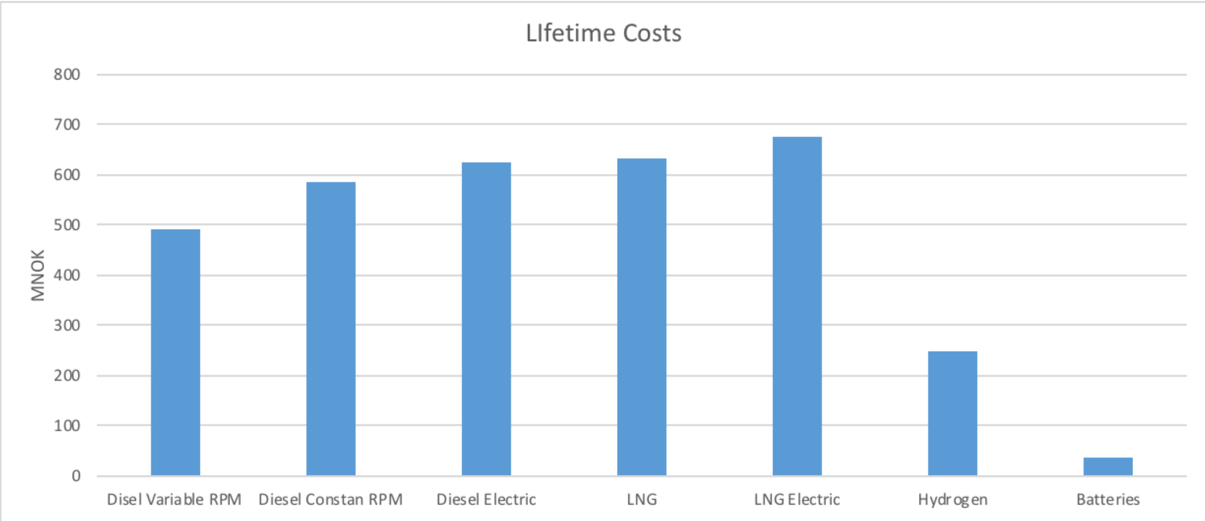


Figure 71 Estimated costs if hydrogen technology costs are dramatically reduced. Note that batteries are not possible to use in this case due to range.

It is anyhow important to note that the student didn´t find any proofs that the numbers described above actually can be realized. If hydrogen fuels are produced from fossil fuels, the production is not sustainable and renewable, and the carbon footprint if CCS-technology isn't used is high.

It is still necessary to develop regulations for use of hydrogen and infrastructure for production, distribution and storage. There are several projects ran to speed up this process and introduce hydrogen as a fuel such as *Statens Vegvesen´s* hydrogen ferry project [56] and several catamaran high-speed passenger vessels [57] [58] [59]. Viking Cruises is also planning to build a hydrogen cruise ship [60]. These projects will most likely lead the way through development of hydrogen powertrains for maritime technology. If the costs and efficiencies are developing as predicted above, it is likely to believe that hydrogen will be a major contributor to maritime transport in the future.

5.5.2 Batteries

So far, batteries are the most common non-fossil powertrain used in ships operating at the Norwegian coast. The development of the car-ferry "*Ampere*" lead the way into using batteries for running ferries crossing fjords. Typical batteries for use in ferries are shown in Figure 72.

This master´s thesis has shown that batteries are the most efficient of the energy carriers considered in this project. By analyzing the results from the passenger vessel and the data provided by Corvus this project has also shown the limitations for batteries. Charging time plays an important role for the lifetime of the batteries. For powertrains designed to supply ships with energy for longer periods without sufficient time in harbor before the operation, it is difficult or not possible to use batteries.

Figure 72 Battery cells from Corvus Energy Storage Systems ESS.

By studying the car ferry version of the tool, it is found that batteries may actually be the most efficient, less pollutant and cheapest powertrain-solution. Therefore, batteries may be the solution for the years to come for this type of ships. If it is assumed that the electricity used to charge the ferry is produced by renewable energy, the carbon footprint from each kWh is low. The student had the pleasure of visiting Corvus Energy Storage Systems ESS at their offices in Bergen. According to them, the technology for screening batteries are also improving.

5.5.3 Hybrid solutions

By combining more than one type of powertrains the advantages for each type can be exploited. According to Mark Kammerer in Hydrogenics it is beneficial for the fuel cell if it is running at constant load. By using batteries for peak shaving the lifetime and efficiency of the fuel cell can be improved. Batteries are also more efficient and by charging when it is possible a higher efficiency can be achieved.

According to Tjalve Magnusson Svendsen in CMR Prototech it is expected that battery- and fuel cell-technology will be working best if combined in ship powertrains. The development of these two technologies are not a threat to each other but a mutual benefit.

5.6 Study trip

Onboard NFT Steigen the project experienced and learned the importance of studying ships that are in operation to be able to say something about the design cycles. Even though NFT Steigen is a state-of-the-art vessel with an efficient powertrain and the newest technology available to ensure cost effective operations, there are still possibilities for further improvements in efficiency. Examples of actions that can be made to improve the efficiency is to replace the harbor generator with a harbor generator with sufficient power for heating at winter time. Another example of improvements that possibly can make a better efficiency is installing batteries for peak shaving. If these improvements are cost effective is not answered in this master thesis.

While the student where onboard NFT Steigen it was observed that the ship constantly changed its schedule for the days to come. The ship was at the most out of harbor for two days. Different harbors were also used, and it is assumed that installing charging capacity to charge the ship in all of these harbors will be expensive. Most of the time when NFT Steigen is in operation, time in harbor is considered "lost money". The purpose of the ship is to move fish from facility to facility and to do lice-removing treatment. Spending sufficient time in harbor to charge batteries is therefore considered less attractive. Batteries as the only energy carrier for most Live Fish Carriers are therefore considered as a less favorable solution.

If the cost development predictions in the previous section becomes a reality, fuel cells are possibly the answer for transition from fossil fuels to renewables for Live Fish Carriers given the engine types studied in this master´s thesis. As shown in Figure 73 hydrogen technology is actually the most cost-effective of the powertrains in this case. LNG also represent a cost-effective solution with less pollution than diesel engines.

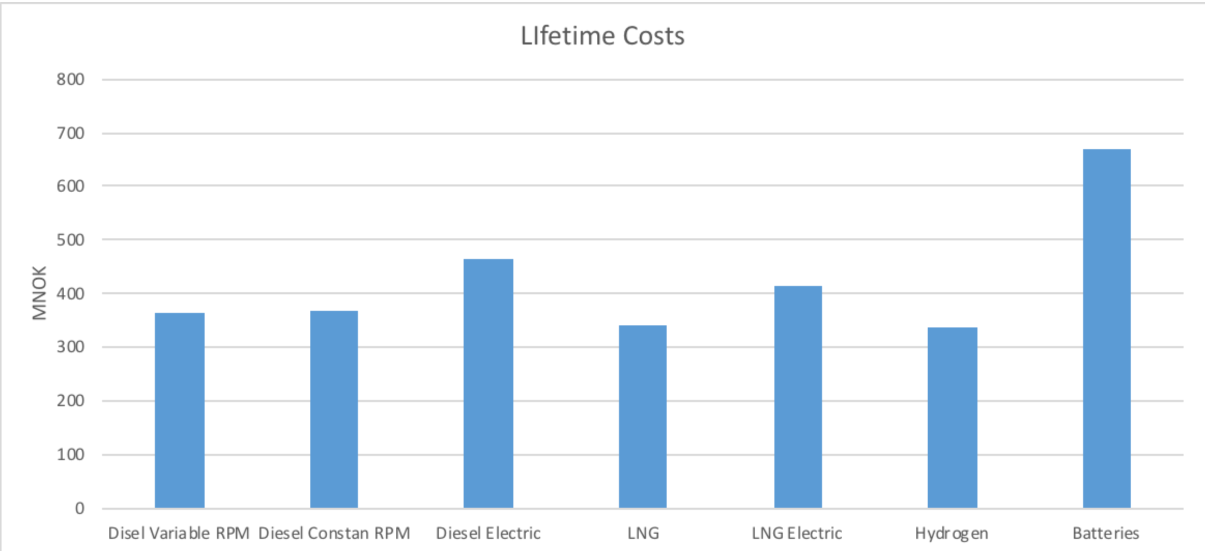


Figure 73 Lifetime costs if hydrogen technology cost decreases as prescribed in the previous section.

The study trip to NFT Steigen was all-in-all a success. Observations done onboard are used to develop the tool and research the possibilities for a green shift in this fleet.

5.7 Future work

The first drafts for this tool were made in September 2016. Since then, the tool has developed step-by-step to what it is today. Completing a tool like this is almost impossible. The rapid development in engine technologies, modern simulation tools and costs are quickly making the tool out of date. Updating engine data and cost values regularly is therefore important.

The list of possible improvements for this tool is long. In the following sections possible developments for each segment will be listed.

5.7.1 Ship design

The tool uses predefined power-speed curves for the ship in operation. There are only a few power-speed curves included in the tool, and most of them are based on admiralty calculations. The measured power-speed curve onboard NFT Steigen shows that the admiralty curve is different from the actual power-speed curve. To have a representative result for vessels it is necessary to have the exact power-speed curve. For users in position with this data it is therefore recommended to overrun the predefined setup and use the exact power-speed data. Future work will be to collect such data and implement in the tool.

The admiralty coefficient is also used to estimate the additional ship resistance added to the ship by weight increase as a result of changing from fossil fuel engines to batteries in the ferry version of the tool. To estimate this, deadweight and lightweight has to be added to the database. Future work will also be to analyze the effect of added deadweight to the ship and hence updating the power-speed curve.

5.7.2 Route studies

Using sea margin and capability to estimate the weather condition for ships is a rough simplification. GYMIR is an analysis tool currently under development of Smart Maritime (a cooperation project founded by the Research Council´s Division for Innovation) [61]. It is a tool assigned to among other things simulate all weather conditions faced by the ship through the year. The student thinks that implementing data from this tool into the tool designed in this master thesis is a reasonable improvement of the routes study part of the tool.

5.7.3 Engine setup

The tool interface limits the number of fossil engines to only one. For most modern ships, more than one engine is used to supply the ship with energy. When several engines are running the ship the efficiency curve different from what it is in this case. By trying to always run the engines at the most efficient load, engines can be turned on and off to obtain this.

The most efficient generalized engine efficiency-curve available with state-of-the-art engine technology can be difficult to estimate. To do this, optimization has to be used by analyzing an unlimited amount of engine setups and calculate which combination that is the most suitable for this ship. Ideally this should also be a logarithm including several inputs such as available space, max weight and eventually the maximum number of engines. Implementing this tool and the corresponding engine database to the tool designed in this master´s would improve the accuracy of the tool dramatically.

A heat recovery input for the tool should have been included in an early stage of the project. Heat recovery represents an important role in increasing the efficiency for ships. A heat recovery setup can be added either by an add-in being a predefined variable defining a percentage of the losses used for powering the ship. Producers of this technology should be contacted to collect data for the available products in the market.

The carbon footprint from production and installation of the different types of engines should also be added to the tool. This would preferably be a predefined editable variable. Many producers of engines do not have precise estimations of the carbon footprint of building, transporting and installing the equipment they have designed. The numbers found by studying life-cycle assessments of carbon footprint are also varying.

Adding predefined variables for well-to-wheel efficiency for the different fuels are necessary to say something about the overall efficiency for the different technologies. The difference between hydrogen and diesel may even when it comes to well-to-wheel efficiency if production, transport and storage of fuels are included in the efficiency.

If CH_4 is released into the atmosphere the impact of this is much worse than CO_2. Therefore, the benefit of using LNG compared to Diesel can disappear if we assume that small amounts of CH_4 is released either through incomplete combustion processes or leakage. An add-in calculating the real effect of CH_4 emissions would be useful in the tool.

5.7.4 Costs

The most important add-in that the student would have added more time were added to the project were estimated developments in fuel costs. It is expected that the carbon tax for fossil fuels will increase in the years to come to reach the 2-degree celsius target. Those taxes may even the price difference between hydrogen and diesel/LNG.

Costs of storage tanks, handling systems, control systems and energy transformers are not included in the tool. These have to be included to give a representative outcome for the lifetime cost estimations.

5.8 General

The method developed in the tool is maybe the most valuable result in this project. By improving different parts in all of the four disciplines the tool can be a very representative tool useful for anyone interested in energy consumption for ships. The tool already includes a complex variety of data and calculations from the four disciplines and it is expected that the outcome is useful for lightening possibilities and limitations for the different systems.

For designers working in early-stage of projects, salesmen, ship-owners and politicians this tool can be used to achieve a better understanding of challenges and possibilities for first of all car ferries, cruise ships and live fish carriers. It is anyhow so that this understanding can be used in discussions for other vessel types as well. This can for example be offshore wind service vessel, platform supply vessels or subsea construction vessels.

The student will after this project work for Havyard Design & Solution in a position as *Designer Performance and Combustion Systems* and work with similar problems for commercial projects. The tool *will* be further developed by the student after hand-in.

In the beginning, six disciplines were included in the tool. Instead of engine setup, load-dependent losses, fuel curves and fuel types and emissions where three different disciplines. The student found it useful to merge these three to “Engine Setup” to simplify the tool.

6. Conclusion

The project has developed a tool with a proper methodology for analyzing the effect of ship design, route studies, engine setup and costs at energy consumption and emissions for ships. The tool has been used to estimate the carbon footprint for the different fuels and to evaluate possible sustainable powertrains for ships.

The results suggest that *batteries* are the best most suitable energy carrier in terms of carbon emissions and costs for double-ended car ferries crossing shorter distances in Norway without considering land infrastructure and carbon footprint from production of batteries. For ferries operating longer distances or for ferries that are dependent on sailing longer distances, hydrogen may be a better alternative.

The results suggest that *hydrogen* may be the best answer for passenger vessels/cruise ships and live fish carriers in the future when considering the energy carriers considered in this tool. With the level of costs for hydrogen technology and hydrogen (fuel) and the available infrastructure today, further developments are necessary if hydrogen are to be used for ships in Norway. If price, efficiency and infrastructure develop as suggested by some, hydrogen is anyhow the clear answer for long distance sailing ships in the future.

There may be developments in the future that can change the numbers and the results found in this master´s thesis dramatically. This can for example be a more rapid increase in carbon tax, new regulations, technology development and more. This thesis does anyhow present a useful basis for comparison.

This master thesis has caught great interest among commercial and non-commercial actors in the market. This is proven by the funding's given to fulfil the project and all the contributors to information and data. As technology and price develops, the results can easily be updated by editing the predefined values in the tool.

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Appendix

A. Passenger Ferry Analysis

Emissions and Efficiency Calculator

Design Number	Havyard 923		LOA	125 m
Project Number	17-144		Breadth	20 m
Vessel Name	TBN		Depth to main deck	fill in m
Vessel Type	Passenger Vessel		Draft	0 m
Owner	Havila Kystruten		Main Engine	7306,2 kW
Operation Area	Norwegian Coast		Shaft generator	fill in kW
			Power supply	fill in
			Year built	fill in
Date printed	27.05.2018		Loading Capacity	700 persons
Verson	1			
Made by	JKO	Date:	27.05.2018	
Verified by		Date:		
Approced by		Date:		

SHEET A	FRONT PAGE	
SHEET B1	VARIABLES	*Simple*
SHEET B2	VARIABLES	*Predefined variables (advanced setup)*
SHEET C	RESULTS	
SHEET D	SHIP DESIGN	
SHEET E	ROUTE STUDIES	
SHEET F	ENGINE SETUP	
SHEET G	COST AND ASSEMBLY	

This report is an energy analysis of the ship design specified above. Theoretical models and simulations are used to produce the current results. The model is ment to be a tool to evaluate different energy systems for a ship design. It contains data for efficiencies, losses, emissions, costs and more. The tool is not to be used as documentation of real-time performance, but for guidance for customer and end-user. The model was produced as a masterthesis at UiB august 2017-june 2018. No data in the report are representative for Havyard Group ASA's designs. To get the latest update, please send an email to jorgen.kopperstad@gmail.com

Project	17-144
Ship name	TBN

B. VARIABLES - Simple Setup

Ship Design

	Unit		
Passengers	n	700	

Max Battery Size		kWh
Sea margin level	2	
Capability level	1	

Route Study

	Harbour	*Shore Charging [kW]*	*Time in port [min]*	*Transit to next port [min]*	*Distance to next port [nm]*
Port 1	Bergen	1400,00	480,00		
Port 2	Florø		15,00	360,00	88,00
Port 3	Måløy		15,00	150,00	28,00
Port 4	Torvik		15,00	180,00	39,00
Port 5	Ålesund		180,00	75,00	15,00
Port 6	Molde		30,00	180,00	35,00
Port 7	Kristiansund		45,00	225,00	48,00
Port 8	Trondheim	1400,00	360,00	420,00	91,00
Port 9	Rørvik		30,00	525,00	125,00
Port 10	Brønnøysund		15,00	210,00	46,00
Port 11	Sandnessjøen		30,00	165,00	36,00
Port 12	Nesna		5,00	70,00	15,00
Port 13	Ørnes		15,00	225,00	51,00
Port 14	Bodø	1400,00	150,00	180,00	39,00
Port 15	Stamsund		30,00	240,00	55,00
Port 16	Svolvær		60,00	90,00	20,00
Port 17	Stokmarknes		15,00	180,00	35,00
Port 18	Sortland		15,00	90,00	15,00
Port 19	Risøyhamn		15,00	75,00	18,00
Port 20	Harstad		60,00	135,00	27,00
Port 21	Finnsnes		30,00	195,00	44,00
Port 22	Tromsø	1400,00	255,00	165,00	37,00
Port 23	Skjervøy		15,00	240,00	53,00
Port 24	Øksfjord		15,00	195,00	45,00
Port 25	Hammerfest		45,00	180,00	41,00
Port 26	Havøysund		30,00	165,00	37,00
Port 27	Honningsvåg	1400,00	210,00	120,00	28,00
Port 28	Kjøllefjord		15,00	135,00	29,00
Port 29	Mehamn		15,00	120,00	26,00
Port 30	Berlevåg		15,00	150,00	36,00
Port 31	Båtsfjord		30,00	90,00	23,00
Port 32	Vardø		15,00	180,00	39,00
Port 33	Vadsø		30,00	195,00	42,00
Port 34	Kirkenes		210,00	105,00	24,00

Project	17-144
Ship name	TBN

B2. VARIABLES - Predefined variables/functions

Ship Design

Ship Power Speed Curve setting: Automatic

	constant	x	x^2	x^3	x^4	x^5	x^6
Ship-Power Curve	-9E-13	4E-13	-3E-14	1E+00			

	L_{OA}	L_{PP}	L_{WL}	Breadth	Draft	Deadwgt.	Lightwgt	Ballast	Service Area
Dimensions	125	na	na	20	0	na	na	na	2

	Harbour	Entering harbour	Leaving Harbour	Acceleration	Passive retardation	Active retardation
Operational Loads	0	1500,00	1500,00	4000	1000	1500

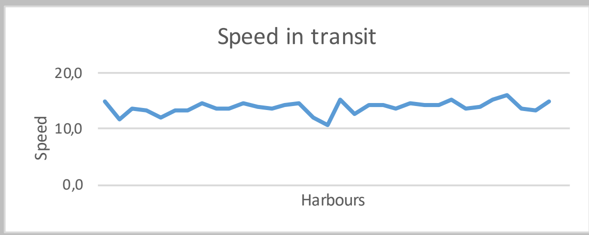
Route Studies

Average Speed 13,9 knots | *Sea Service Area Margin* 12,00 % | *Design speed* 15,00 knots

	Time [s]	*kW*	*kWh*
Leaving Harbour	60,0	1500,0	25,0
Acceleration	240,0	4000,0	266,7
Passive Retardation	120,0	1000,0	33,3
Active retardation	240,0	1500,0	100,0
Entering Harbour	240,0	1500,0	100,0

Design Capability 20,0 %

Design max speed 17 *knots*



Engine Setup

Max Power 7306,2 kW

Design Speed Power 3500 kW

Battery lifetime 10 *years*

Hotel Load 750 kW

	Generator	*Drives/Converter*	*DC/DC Converters*	*Switchboard*	*El-motors*	*Gear*	*Cabling*	*Open*
Losses	5 %	5 %	5 %	3 %	5,9 %	5 %	3 %	0 %

Emissions

	CO_2 per kg fuel, kg	*Nox per kWh, g*	*CO per kWh, g*	*PM per kWh, g*	*SO per kWh, g*
Diesel Variable RPM	3,17	7,85	5	0,5	1
Diesel Constant RPM	3,17	7,85	5	0,5	1
LNG Constant RPM	2,76	1,5	0,05	0,005	0,01

Project	17-144
Ship name	TBN

C. RESULTS

Emissions per tour

	CO_2 [t]	NO_x [kg]	PM [kg]	SO [kg]	CO [kg]	Carbon Footprint [t]
Diesel variable RPM	336	3662	233	466	2332	378
Diesel Constant RPM	345	3662	233	466	2332	388
Diesel Constant RPM (Diesel-Electric)	391	4203	268	535	2615	441
LNG Constant RPM	236	826	3	6	28	271
LNG Constant RPM (LNG-Electric)	230	803	3	5	36	266
Hydrogen						96
Batteries	Na	Na	Na	Na	Na	28

In addition comes the emissions from producing the engine. These are not included in the calculations

Consumptions per tour

	Fuel [kg]	Energy, fuel [kWh]	Energy, electricity [kWh]	Used [kWh]	Incl WTWE [kWh]
Diesel variable RPM	105854	1267076		1267076	NA
Diesel Constant RPM	108794	1302258		1302258	NA
Diesel Constant RPM (Diesel-Electric)	123236	1475129	33950	1509079	NA
LNG Constant RPM	85574	1189702		1189702	NA
LNG Constant RPM (LNG-Electric)	83616	1162896	33950	1196846	NA
Hydrogen	27848	1130628	33800	1164428	NA
Batteries	Na		558775	558775	NA

Lifetime Costs estimation

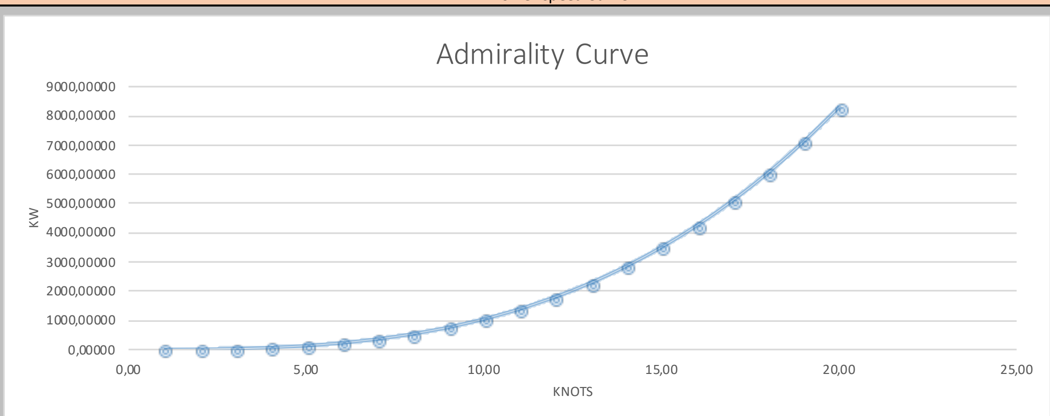
Diesel Var.	Diesel const	Diesel-Battery	LNG Const	LNG-Battery	Batteries	Hydrogen
493	506	627	553	675	1971	39

Battery setup

	Shore Charging	kWh	Left for nex	Necessary to next harbour [kW]
Bergen	1400	4028	No left	5428
Florø	0	0	No left	36793
Måløy	0	0	No left	59254
Torvik	0	0	No left	26296
Ålesund	0	0	No left	3870
Molde	0	0	No left	34465
Kristiansund	0	0	No left	41602
Trondheim	1400	3021	No left	8041
Rørvik	0	0	No left	34574
Brønnøysund	0	0	No left	56118
Sandnessjøen	0	0	No left	14879
Nesna	0	0	No left	238762
Ørnes	0	0	No left	59254
Bodø	1400	1259	No left	8641
Stamsund	0	0	No left	18830
Svolvær	0	0	No left	11611
Stokmarknes	0	0	No left	20338
Sortland	0	0	No left	34136
Risøyhamn	0	0	No left	39275
Harstad	0	0	No left	17436
Finnsnes	0	0	No left	29956
Tromsø	1400	2140	No left	4649
Skjervøy	0	0	No left	73667
Øksfjord	0	0	No left	66784
Hammerfest	0	0	No left	19971
Havøysund	0	0	No left	25855
Honningsvåg	1400	1762	No left	3301
Kjøllefjord	0	0	No left	43183
Mehamn	0	0	No left	65676
Berlevåg	0	0	No left	46022
Båtsfjord	0	0	No left	29627
Vardø	0	0	No left	62442
Vadsø	0	0	No left	22350
Kirkenes	na	na	na	na

Project	17-144	D. SHIP DESIGN - Ferry
Ship name	TBN	

Power-speed Curve



Main Dimensions

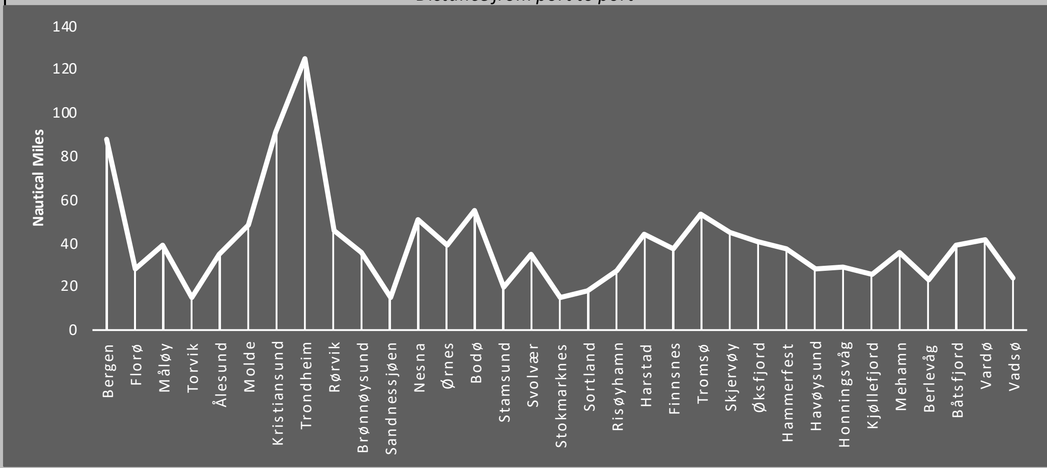
	L_{OA}	L_{PP}	L_{WL}	Breadth	Draught	Deadwgt.	Lightwgt	Ballast	Service Area
Dimensions	125	na	na	20	0	na	na	na	2

Project	17-144	E. ROUTE STUDIES
Ship name	TBN	

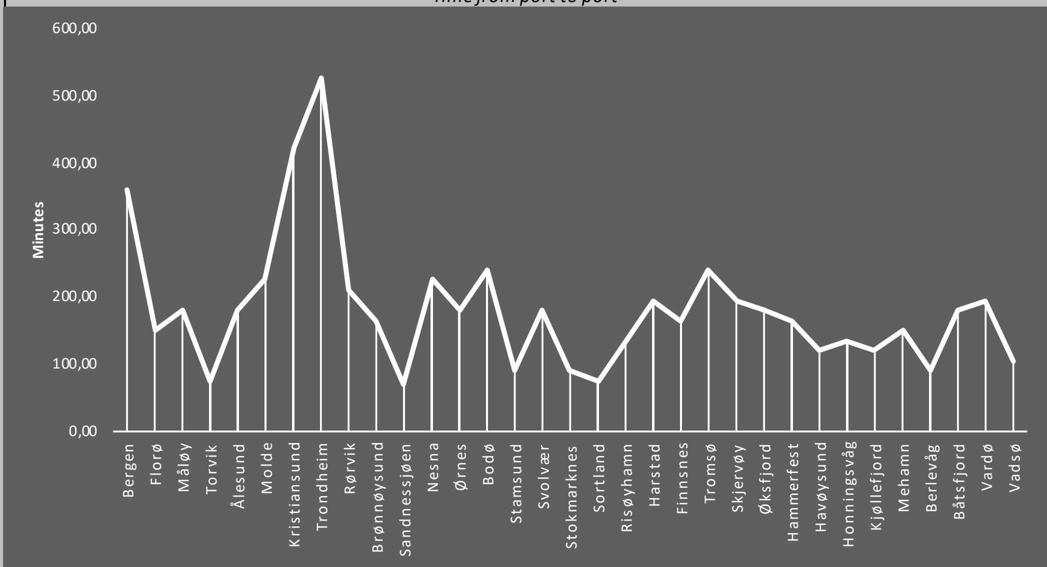
Input from simple setup - route studies

Number of design routes per year 60,6

Distance from port to port



Time from port to port



Capabilites and Sea Margin

Capabilites			Sea Margin	
Level	%		Level	%
1	20		1	5
2	40		2	12
3	70		3	18
4	100		4	40

Project	17-144
Ship name	TBN

F. ENGINE SETUP

Efficiency, propulsion

	Diesel Var.	Diesel const	Diesel-Battery	LNG Const	LNG-Battery	Batteries	Hydrogen
Generator	no	no	yes	yes	yes	no	no
Drives/Converter	no	no	yes	yes	yes	yes	yes
Cabling	no	no	yes	yes	yes	yes	yes
Switchboard	no	no	yes	yes	yes	yes	yes
El-motors	no	no	yes	yes	yes	yes	yes
DC/DC converters	no	no	no	no	no	no	yes
Gear	yes	yes	yes	yes	yes	yes	yes
Overall	95,00 %	95,00 %	75,91 %	75,91 %	75,91 %	79,91 %	75,91 %

Efficiency, electricity production

	Diesel Var.	Diesel const	Diesel-Battery	LNG Const	LNG-Battery	Batteries	Hydrogen
Generator	yes	yes	yes	yes	yes	yes	yes
Drives/converter	yes	yes	yes	yes	yes	yes	yes
Cabling	yes	yes	yes	yes	yes	yes	yes
Switchboard	yes	yes	yes	yes	yes	yes	yes
DC/DC Converters	no	no	no	no	no	no	yes
Open	no	no	no	no	no	no	no
Overall	84,92 %	84,92 %	84,92 %	84,92 %	84,92 %	84,92 %	80,67 %

Efficiency, fossile fuels

	Const	x	x^2	x^3	x^4	x^5	x^6
Diesel Variable RPM	0,3099	0,58	-4,0844	15,441	-29,665	27,841	-10,15
Diesel Constant RPM	0,1667	1,1482	-3,1976	5,072	-4,1771	1,3626	
LNG	0,1406	1,7576	-3,8877	4,04E+00	-1,56E+00		

Efficiency, electricity production, Hydrogen

Max power	6720,00		Number of cells	56,00		54,00 %	until	1960	kW
Hours of operation	25000	h	Peak Efficiency kW	35					
Design lifetime	4,00	years	Weight	20160	kg				
Design Stack Size	120	kW	Cost cells	87,36	MNOK				

From max efficiency to mac performance

const	x	x^2	x^3	x^4
0,44	0,84	-2,54	2,96	-1,25

Efficiency, electricity production, Batteries

			Cost	27,49	MNOK
			Design Capacity	5034,77	kWh
Cycluses	3031,56		*Number of stacks*	37,13	Stacks
Allowed discharge	80%	%	*Weight of stacks*	65422,25	kg

Power	2517,38	5034,766	7552,15	10069,5	12586,9	15104,29693
Losses	0,95 %	1,75 %	2,55 %	3,50 %	4,30 %	5,25 %

Minutes in harbour for charging	5,00	min
	480	max
Is batteries possible with the current setup?	No	

Carbon footprint and well to wheel efficiency fromproduction

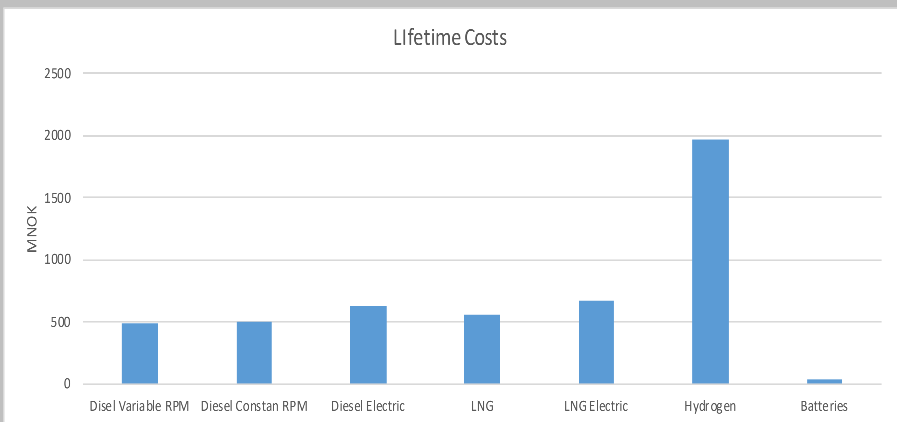
	CO2-equivalents	Well to wheel efficiency
	per kg fuel, g	%
Diesel variable rpm	*397,22*	
LNG	*407,84*	
Electricity, Norwegian mix	50	

Project	17-144	
Ship name	TBN	

G. COST AND ASSEMBLY

Price development and investments

	Disel Variable RPM		Diesel Constan RPM		Diesel Electric		LNG		LNG Electric		Hydrogen		Batteries	
	CAPEX	OPEX	CAPEX	OPEX	CAPEX	OPEX	CAPEX	OPEX	CAPEX	OPEX	CAPEX	OPEX	CAPEX	OPEX
1	21,9	44,56	21,9	45,80	57,4	52,50	73,1	45,80	108,6	52,50	122,9	157,26	27,5	0,00
2	0	44,56	0	45,80	0	52,50	0	45,80	0	52,50	0	157,26	0	0,00
3	0	44,56	0	45,80	0	52,50	0	45,80	0	52,50	0	157,26	0	0,00
4	0	44,56	0	45,80	0	52,50	0	45,80	0	52,50	0	157,26	0	0,00
5	0	44,56	0	45,80	0	52,50	0	45,80	0	52,50	87,36	157,26	0	0,00
6	0	44,56	0	45,80	0	52,50	0	45,80	0	52,50	0	157,26	0	0,00
7	0	44,56	0	45,80	0	52,50	0	45,80	0	52,50	0	157,26	0	0,00
8	0	44,56	0	45,80	0	52,50	0	45,80	0	52,50	0	157,26	0	0,00
9	0	44,56	0	45,80	0	52,50	0	45,80	0	52,50	87,36	157,26	0	0,00
10	0	44,56	0	45,80	0	52,50	0	45,80	0	52,50	0	157,26	0	0,00
11	0	44,56	0	45,80	35,49	52,50	0	45,80	35,49	52,50	35,49	157,26	27,4898	0,00
12	0	44,56	0	45,80	0	52,50	0	45,80	0	52,50	0	157,26	0	0,00
13	0	44,56	0	45,80	0	52,50	0	45,80	0	52,50	87,36	157,26	0	0,00
14	0	44,56	0	45,80	0	52,50	0	45,80	0	52,50	0	157,26	0	0,00
15	0	44,56	0	45,80	0	52,50	0	45,80	0	52,50	0	157,26	0	0,00
16	0	44,56	0	45,80	0	52,50	0	45,80	0	52,50	0	157,26	0	0,00
17	0	44,56	0	45,80	0	52,50	0	45,80	0	52,50	87,36	157,26	0	0,00
18	0	44,56	0	45,80	0	52,50	0	45,80	0	52,50	0	157,26	0	0,00
19	0	44,56	0	45,80	0	52,50	0	45,80	0	52,50	0	157,26	0	0,00
20	0	44,56	0	45,80	0	52,50	0	45,80	0	52,50	0	157,26	0	0,00
Costs		492,534		505,6414		626,7483		553,439		674,546		1971,395252		38,7516



	Average price	*NOK*		*NOK*		*MNOK*		*NOK*
MGO	Price per kWh	0,58	Price per kW	3000	Lifetime	20	Maintenance per year per kW	0
LNG	Price per kWh	0,58	Price per kW	10000	Lifetime	20	Maintenance per year per kW	0
Hydrogen	Price per kWh	2,28	Price per kW	13000	Lifetime	4,00	Maintenance per year per kW	0
Batteries	Price per kWh	0,57	Price per kWh	5460	Lifetime	10,00	Maintenance per year per kWh	0

Interest 7 %

B. Ferry Analysis

Emissions and Efficiency Calculator				
Design Number	Havyard		LOA	fill in m
Project Number	Hareid Sulesund Ferry		Breadth	fill in m
Vessel Name	TBN		Depth to main deck	fill in m
Vessel Type	Double ended Car Ferry		Draft	fill in m
Owner	TBA		Main Engine	2821 kW
Operation Area	Hareid-Sulesund		Shaft generator	fill in kW
			Power supply	to be filled in
			Year built	fill in
Date printed	27.05.2018		Loading Capacity	120 PBE
Verson	1			
Made by	JKO	Date:	27.05.2018	
Verified by		Date:		
Approced by		Date:		
SHEET A	FRONT PAGE			
SHEET B1	VARIABLES		*Simple*	
SHEET B2	VARIABLES		*Predefined variables (advanced setup)*	
SHEET C	RESULTS			
SHEET D	SHIP DESIGN			
SHEET E	ROUTE STUDIES			
SHEET F	ENGINE SETUP			
SHEET G	COST AND ASSEMBLY			

This report is an energy analysis of the ship design specified above. Theoretical models and simulations are used to produce the current results. The model is ment to be a tool to evaluate different energy systems for a ship design. It contains data for efficiencies, losses, emissions, costs and more. The tool is not to be used as documentation of real-time performance, but for guidance for customer and end-user. The model was produced as a masterthesis at UiB august 2017-june 2018. No data in the report are representative for Havyard Group ASA's designs. To get the latest update, please send an email to jorgen.kopperstad@gmail.com

Project	Hareid Sules
Ship name	TBN

B1. VARIABLES - Simple Setup

Ship Design

	Unit				
Cars/Personbileiningar	PBE	120	*Forced Battery Charging Capacity* *(Only for hybridization)*	500,00	kWh

Route Study

	Unit				
Number of ports	n	3	Max Speed With Current Schedule	15,9	*knots*
			Is this less thant the max speed?	Yes	
			Are there sufficient charging for batteries?	Yes	

	Shore Charging [kW]	*Time in port [min]*	*Transit to next port [min]*	*Distance to next port [nm]*
Port 1	4000,00	10,00	20,00	4,00
Port 2	4000,00	10,00	19,00	4,00
Port 3	4000,00	10,00	22,00	4,00

	Unit	
Number of roundtrips per day	n	18,00
Sea margin level [Serice Area]	1,2,3,4	1
Capability level [Serice Area]	1,2,3,4	3

Project	Hareid Sules
Ship name	TBN

B2. VARIABLES - Predefined variables/functions

Ship Design

Ship Power Speed Curve Setting Automatic

	constant	x	x^2	x^3
Ship-Power Curve	8E-01	0E+00	8E-01	8,5E-01

	L_{OA}	L_{PP}	L_{WL}	Breadth	Draft	Deadwgt.	Lightwgt	Ballast	Service Area
Dimensions	125	na	na	20	0	na	na	na	1

	Loading	Entering harbour	Leaving Harbour	Acceleration	Passive retardation	Active retardation
Operational Loads	*0*	350,00	250,00	700	55	200
Connected to shore	*yes*	no	no	no	no	no

Route Studies

Capability 70,00 %

Sea Service Area Margin 5,00 %

Minutes in port 258

Minutes at sea 1182

Time in different ports [s]

	Shore	Loading	Entering harbour	Leaving Harbour	Acceleration	Passive retardation	Active retardation
Port 1		*600*	90	30	124,00	120	30
Port 2		*600*	90	30	124,00	120	30
Port 3		*600*	90	30	124,00	120	30

Design speed 12,00 knots

Distance for maneuvring *0,7* *nm*

Max Speed *16* *knots*

Engine Setup

Max Power *2820,7* *kW*

Design Speed Power *700* *kW*

Hotel Power *60* *kW*

	Generator	*Drives/Converter*	*DC/DC Converters*	*Switchboard*	*El-motors*	*Gear*	*Cabling*	*Open*
Losses	*5 %*	*5 %*	*5 %*	*3 %*	*5,9 %*	*5 %*	*3 %*	*0 %*

Emissions

	CO_2 per kg fuel, kg	*Nox per kWh, g*	*CO per kWh, g*	*PM per kWh, g*	*SO per kWh, g*
Diesel Variable RPM	*3,17*	*7,85*	*5*	*0,5*	*1*
Diesel Constant RPM	*3,17*	*7,85*	*5*	*0,5*	*1*
LNG Constant RPM	*2,76*	*1,5*	*0,05*	*0,005*	*0,01*

Project	Hareid Sulesun
Ship name	TBN

C. RESULTS

Daily emissions

	CO_2 [kg]	NO_x [g]	CO [g]	PM [g]	SO [g]	Carbon Footprint [t]
Diesel variable RPM	14940	77818	102678	10268	20536	16
Diesel Constant RPM - Hybrid	15609	77818	102678	10268	20536	16
Diesel Constant RPM (Diesel-Electric)	10693	57819	70972	7097	14194	13
LNG Constant RPM - Hybrid	10365	31704	1057	106	211	11
LNG Constant RPM (LNG-Electric)	6086	20353	678	68	136	8
Hydrogen	0	0	0	0	0	4
Batteries	0	0	0	0	0	1

In addition comes the emissions from producing the engine. These are not included in the calculations

Daily Consumptions

	Fuel [kg]	Energy, fuel [kWh]	Energy, electricity [kWh]	Used [kWh]	Incl WTWE [kWh]
Diesel variable RPM	2034,0	56757		56757	NA
Diesel Constant RPM	2173,1	59281		59281	NA
Diesel Constant RPM (Diesel-Electric)	1625,1	76376	35460	111836	NA
LNG Constant RPM	1612,5	48135		48135	NA
LNG Constant RPM (LNG-Electric)	1130,2	30571	35460	66031	NA
Hydrogen	359,3	28653	35460	64113	NA
Batteries	0		24341	24341	NA

Hybridization

	Diesel Hybrid		LNG Hybrid		Hydrogen	
	% Battery	kWh	% Battery	kWh	% Battery	kWh
Port 1	28,03 %	770,21	34,1 %	580,11	35,2 %	551,71
Port 2	24,04 %	947,66	29,7 %	709,25	29,6 %	714,80
Port 3	36,35 %	525,23	42,5 %	405,53	47,1 %	336,31

BATTERIES

	Available Charging	Need	Is it enough?
Port 1	656,667	464,4373	Yes
Port 2	656,667	528,3955	Yes
Port 3	656,667	369,9176	Yes
	0	0	Yes
	0	0	Yes

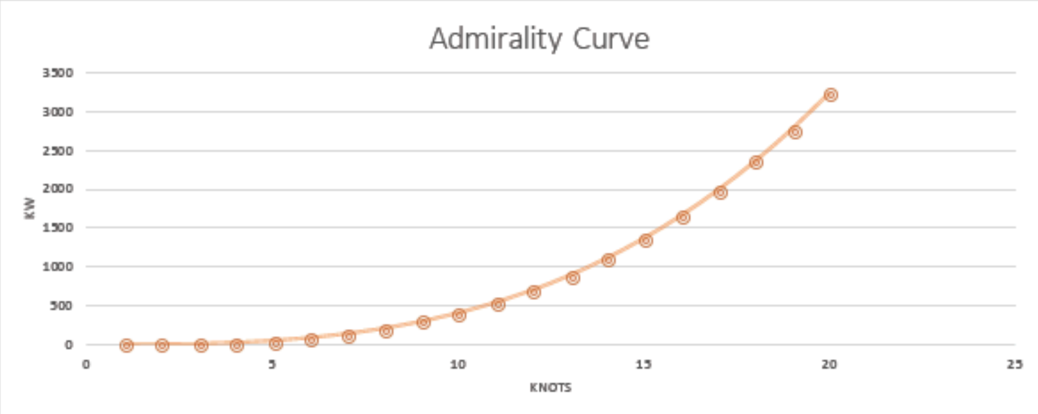
Lifetime Costs estimation

Diesel Var.	Diesel const	Diesel-Battery	LNG Const	LNG-Battery	Batteries	Hydrogen
135	141	189	134	183	430	80

Project	Harald Sules
Ship name	TBN

D. SHIP DESIGN - Ferry

Power-speed Curve



Main Dimensions

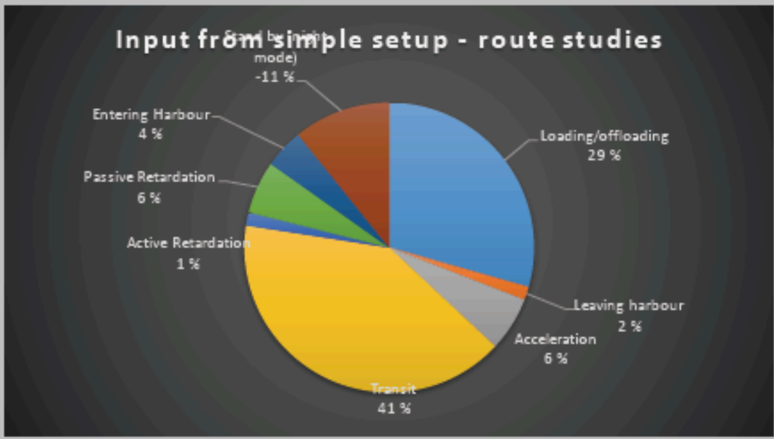
	L_{OA}	L_{PP}	L_{WL}	Breadth	Draught	Deadwgt.	Lightwgt	Ballast	Service Area
Dimensions	125	na	na	20	0	na	na	na	1

Project	Hareid Sules
Ship name	TBN

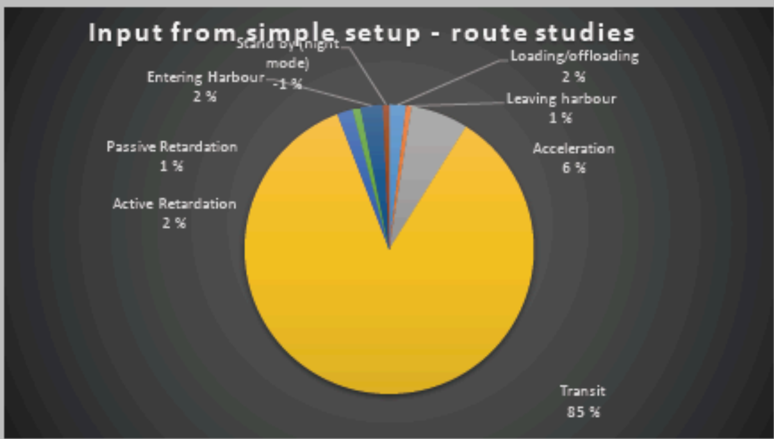
E. ROUTE STUDIES

Input from simple setup - route studies

Loading/offloading	540,00	min
Leaving harbour	27,00	min
Acceleration	111,60	min
Transit	743,40	min
Active Retardation	27,00	min
Passive Retardation	108,00	min
Entering Harbour	81,00	min
Stand by (night mode)	-198	min



Loading/offloading	540,00	kWh
Leaving harbour	180,00	kWh
Acceleration	1846,59	kWh
Transit	24529,51	kWh
Active Retardation	501,19	kWh
Passive Retardation	257,60	kWh
Entering Harbour	717,83	kWh
Stand by (night mode)	-198,00	kWh



Capabilites and Sea Margin

Capabilites	
Level	%
1	20
2	40
3	70
4	100

Sea Margin	
Level	%
1	5
2	12
3	18
4	40

Project	Hareid Sules
Ship name	TBN

F. ENGINE SETUP

Efficiency, propulsion

	Diesel Var.	Diesel const	Diesel-Battery	LNG Const	LNG-Battery	Batteries	Hydrogen
Generator	no	no	yes	yes	yes	no	no
Drives/Converter	no	no	yes	yes	yes	yes	yes
Cabling	no	no	yes	yes	yes	yes	yes
Switchboard	no	no	yes	yes	yes	yes	yes
El-motors	no	no	yes	yes	yes	yes	yes
DC/DC converters	no	no	no	no	no	no	yes
Gear	yes	yes	yes	no	no	yes	yes
Overall	95,00 %	95,00 %	75,91 %	79,91 %	79,91 %	79,91 %	75,91 %

Efficiency, electricity production

	Diesel Var.	Diesel const	Diesel-Battery	LNG Const	LNG-Battery	Batteries	Hydrogen
Generator	yes	yes	yes	yes	yes	no	no
Drives/converter	yes	yes	yes	yes	yes	yes	yes
Cabling	yes	yes	yes	yes	yes	yes	yes
Switchboard	yes	yes	yes	yes	yes	yes	yes
DC/DC Converters	no	no	yes	yes	yes	yes	yes
Open	no	no	yes	yes	yes	yes	no
Overall	84,92 %	84,92 %	80,67 %	80,67 %	80,67 %	84,92 %	84,92 %

Efficiency, fossile fuels

	Const	x	x^2	x^3	x^4	x^5	x^6
Diesel Variable RPM	0,3099	0,58	-4,0844	15,441	-29,665	27,841	-10,15
Diesel Constant RPM	0,1667	1,1482	-3,1976	5,072	-4,1771	1,3626	
LNG	0,1406	1,7576	-3,8877	4,04E+00	-1,56E+00		

Efficiency, electricity production, Hydrogen

Max power	1746,59	Number of cells	15,00		54% until	525	kW
Hours of operation	25000 h				Peak Power efficiency	35	kW
Design lifetime	3,00 years	Weight	5400	kg	Peak Efficiency	54 %	
Design Stack Size	120 kW	Cost cells	23,25	MNOK			

From max efficiency to mac performance

const	x	x^2	x^3	x^4
0,44	0,84	-2,54	2,96	-1,25

Efficiency, electricity production, Batteries

Design lifetime	10	years	*Design Capacity*	3357,01	kWh
Cycluses	19710		*Number of stacks*	24,76	Stacks
Allowed discharge	40	%	*Weight of stacks*	43621,34	kg

Power	1678,51	3357,011	5035,52	6714,02	8392,53	10071,034
Losses	0,95 %	1,75 %	2,55 %	3,50 %	4,30 %	5,25 %

Carbon footprint and well to wheel efficiency fromproduction

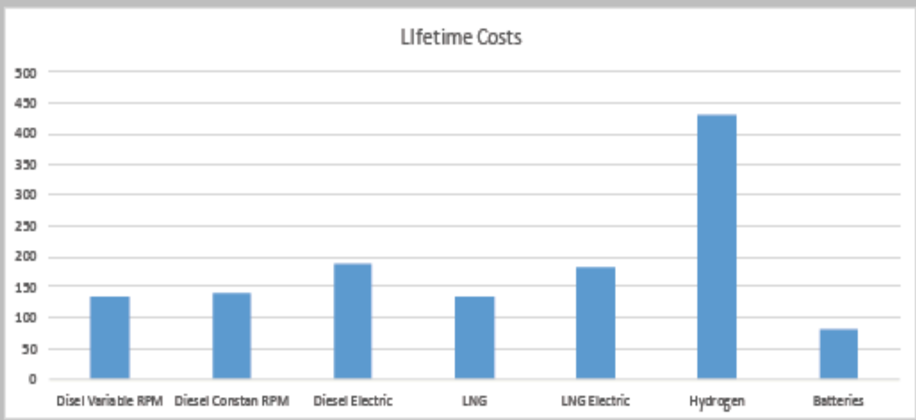
	CO2-equivalents	Well to wheel efficiency
	per kg fuel, g	%
Diesel variable rpm	*397,22*	
LNG	*407,84*	
Electricity, Norwegian mix	50	

Project	Harald Sule
Ship name	TBN

G. COST AND ASSEMBLY

Price development and investments

	Disel Variable RPM		Diesel Constan RPM		Diesel Electric		LNG		LNG Electric		Hydrogen		Batteries	
	CAPEX	OPEX	CAPEX	OPEX	CAPEX	OPEX	CAPEX	OPEX	CAPEX	OPEX	CAPEX	OPEX	CAPEX	OPEX
1	8,5	12,02	8,5	12,55	12,56	16,58	28,21	10,19	35,03	13,89	29,53	31,39	18,33	5,10
2	0	12,02	0	12,55	0,00	16,58	0,00	10,19	0,00	13,89	0,00	31,39	0,00	5,10
3	0	12,02	0	12,55	0,00	16,58	0,00	10,19	0,00	13,89	0,00	31,39	0,00	5,10
4	0	12,02	0	12,55	0,00	16,58	0,00	10,19	0,00	13,89	22,71	31,39	0,00	5,10
5	0	12,02	0	12,55	0,00	16,58	0,00	10,19	0,00	13,89	0,00	31,39	0,00	5,10
6	0	12,02	0	12,55	0,00	16,58	0,00	10,19	0,00	13,89	0,00	31,39	0,00	5,10
7	0	12,02	0	12,55	0,00	16,58	0,00	10,19	0,00	13,89	22,71	31,39	0,00	5,10
8	0	12,02	0	12,55	0,00	16,58	0,00	10,19	0,00	13,89	0,00	31,39	0,00	5,10
9	0	12,02	0	12,55	0,00	16,58	0,00	10,19	0,00	13,89	0,00	31,39	0,00	5,10
10	0	12,02	0	12,55	0,00	16,58	0,00	10,19	0,00	13,89	22,71	31,39	0,00	5,10
11	0	12,02	0	12,55	4,10	16,58	0,00	10,19	6,83	13,89	6,83	31,39	18,33	5,10
12	0	12,02	0	12,55	0,00	16,58	0,00	10,19	0,00	13,89	0,00	31,39	0,00	5,10
13	0	12,02	0	12,55	0,00	16,58	0,00	10,19	0,00	13,89	22,71	31,39	0,00	5,10
14	0	12,02	0	12,55	0,00	16,58	0,00	10,19	0,00	13,89	0,00	31,39	0,00	5,10
15	0	12,02	0	12,55	0,00	16,58	0,00	10,19	0,00	13,89	0,00	31,39	0,00	5,10
16	0	12,02	0	12,55	0,00	16,58	0,00	10,19	0,00	13,89	22,71	31,39	0,00	5,10
17	0	12,02	0	12,55	0,00	16,58	0,00	10,19	0,00	13,89	0,00	31,39	0,00	5,10
18	0	12,02	0	12,55	0,00	16,58	0,00	10,19	0,00	13,89	0,00	31,39	0,00	5,10
19	0	12,02	0	12,55	0,00	16,58	0,00	10,19	0,00	13,89	22,71	31,39	0,00	5,10
20	0	12,02	0	12,55	0,00	16,58	0,00	10,19	0,00	13,89	0,00	31,39	0,00	5,10
Costs		135,2		140,862		189,3154		134,318		183,147		429,751		79,9034



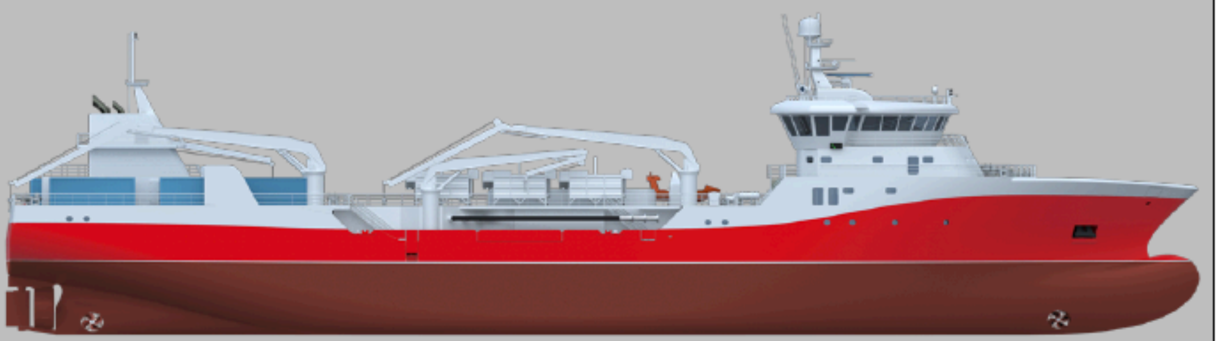
	Average price	NOK		NOK		MNOK		NOK
MGO	Price per kWh	0,58	Price per kW	3000	Lifetime	20	Maintenance per year per kW	0
LNG	Price per kWh	0,58	Price per kW	10000	Lifetime	20	Maintenance per year per kW	0
Hydrogen	Price per kWh	2,28	Price per kW	13000	Lifetime	3,00	Maintenance per year per kW	0
Batteries	Price per kWh	0,57	Price per kWh	5460	Lifetime	10,00	Maintenance per year per kWh	0

Interest	7 %

C. Live fish carrier Analysis

Emissions and Efficiency Calculator					
Design Number	Havyard 587		LOA	fill in m	
Project Number	NA		Breadth	fill in m	
Vessel Name	NFT Steigen		Depth to main deck	fill in m	
Vessel Type	Live Fish Carrier		Draft	fill in m	
Owner	Norsk Fisketransport		Main Engine	4333 kW	
Operation Area	Norwegian Coast		Shaft generator	fill in kW	
			Power supply	fill in	
			Year built	fill in	
Date printed	27.05.2018		Loading Capacity	3250 m^3	
Verson	1				
Made by	JKO	Date:	27.05.2018		
Verified by		Date:			
Approced by		Date:			
SHEET A	FRONT PAGE				
SHEET B1	VARIABLES		*Simple*		
SHEET B2	VARIABLES		*Predefined variables (advanced setup)*		
SHEET C	RESULTS				
SHEET D	SHIP DESIGN				
SHEET E	ROUTE STUDIES				
SHEET F	ENGINE SETUP				
SHEET G	COST AND ASSEMBLY				

This report is an energy analysis of the ship design specified above. Theoretical models and simulations are used to produce the current results. The model is ment to be a tool to evaluate different energy systems for a ship design. It contains data for efficiencies, losses, emissions, costs and more. The tool is not to be used as documentation of real-time performance, but for guidance for customer and end-user. The model was produced as a masterthesis at UiB august 2017-june 2018. To get the latest update, please send an email to jorgen.kopperstad@gmail.com



Project	NA
Ship name	NFT Steigen

B. VARIABLES - Simple Setup

Ship Design

	Unit		
Water	m^3	3250	

Minimum % of battery power 15,00 %

Route Study

	Hours per month	*31 days*
Standby in Harbour	72	*hours*
Pulling out	8	*hours*
Transit without cargo, ECO	150	*hours*
Transit without cargo, FULL	30	*hours*
Transit with cargo, ECO	150	*hours*
Transit with cargo, FULL	30	*hours*
Approaching	8	*hours*
Cargo Operations	200	*hours*
Manoeuvring	19	*hours*
Tankwash	47	*hours*
Waiting on facility	10	*hours*
Operational STBY	20	*hours*

Hours per month	744
Left	0

Capability level 2

Sea margin level 1

Design route (Optional)

Pulling out	5	*min*
Transit without cargo, ECO	300	*min*
Transit without cargo, FULL		*min*
Transit with cargo, ECO	600	*min*
Transit with cargo, FULL		*min*
Approaching	20	*min*
Cargo Operations	120	*min*
Manoeuvring	40	*min*
Tankwash	60	*min*
Waiting on facility	30	*min*
Operational STBY		*min*

Project	NA
Ship name	NFT Steigen

B2. VARIABLES - Predefined variables/functions

Ship Design

Ship Power Speed Curve Setting Automatic

Ship-Power Curve	constant	x	x^2	x^3
	8E-01	0E+00	8E-01	8,3E-01

	L_{OA}	L_{PP}	L_{WL}	Breadth	Draught	Deadwgt.	Lightwgt	Ballast	Service Area
Dimensions						8000			1

Operation Power [kW]

Standby in Harbour	280	Transit with cargo, ECO	2300	Manoeuvring	2300
Pulling out	1500	Transit with cargo, FULL	2600	Tankwash	2000
Transit without cargo, ECO	2100	Approaching	2600	Waiting on facility	2600
Transit without cargo, FULL	2600	Cargo Operations	2450	Operational STBY	2000

Route Studies

Design speed	12,0 knots	*Sea Service Area Margin*	5,00 %	*Time in port*	9,68 % %
		Design sea margin, max	40,00 %	*Time at sea*	90,32 % %

Engine Setup

Max Power 4333,3 kW

Design Speed Power 1600 kW

Hotel Load 100 kW

	Generator	Drives/Converter	DC/DC Converters	Switchboard	El-motors	Gear	Cabling	Open
Losses	5 %	5 %	5 %	3 %	5,9 %	5 %	3 %	0 %

Power only for propulsion

Standby in Harbour	0	Transit with cargo, ECO	1800	Manoeuvring	1200
Pulling out	1300	Transit with cargo, FULL	2500	Tankwash	400
Transit without cargo, ECO	1500	Approaching	800	Waiting on facility	400
Transit without cargo, FULL	2450	Cargo Operations	0	Operational STBY	400

Emissions

	CO_2 per kg fuel, kg	Nox per kWh, g	CO per kWh, g	PM per kWh, g	SO per kWh, g
Diesel Variable RPM	3,17	7,85	5	0,5	1
Diesel Constant RPM	3,17	7,85	5	0,5	1
LNG Constant RPM	2,76	1,5	0,05	0,005	0,01

Project	NA
Ship name	NFT Steigen

C. RESULTS

Daily emissions

	CO_2 [kg]	NO_x [kg]	PM [kg]	SO [kg]	CO [kg]	Carbon Footprint [t]	
Diesel variable RPM	41655	457	29	13	291	47	In addition comes the emissions from producing the engine. These are not included in the calculations
Diesel Constant RPM	41840	449	29	13	286	47	
Diesel Constant RPM (Diesel-Electric)	39951	430	27	13	274	45	
LNG Constant RPM	26980	96	0	0	3	31	
LNG Constant RPM (LNG-Electric)	27014	82	0	0	3	32	
Hydrogen	NA	NA	NA	NA	NA	10	
Batteries	NA	NA	NA	NA	NA	3	

Daily Consumptions

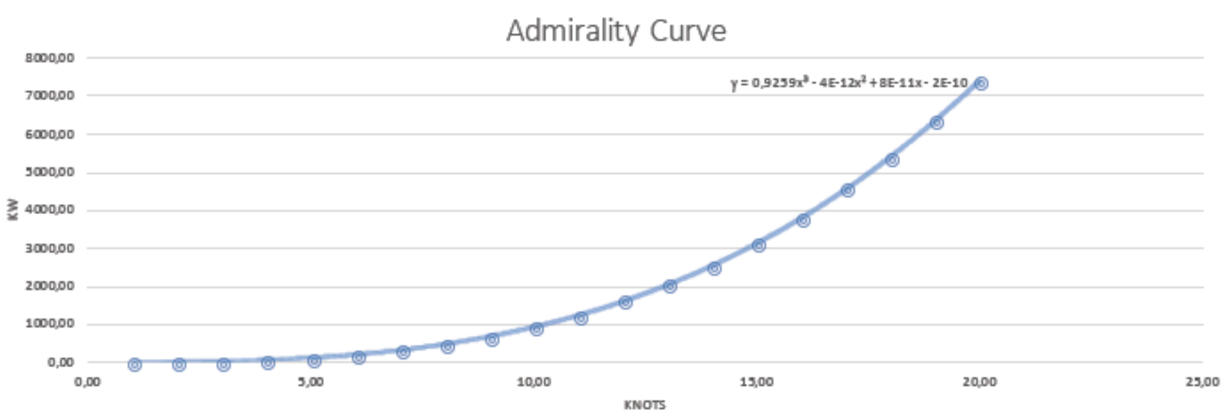
	Fuel [kg]	Energy, fuel [kWh]	Energy, electricity [kWh]	Used [kWh]	Incl WTWE [kWh]
Diesel variable RPM	13140	157		157	NA
Diesel Constant RPM	13199	158		158	NA
Diesel Constant RPM (Diesel-Electric)	12603	151	11	161	NA
LNG Constant RPM	9790	134		134	NA
LNG Constant RPM (LNG-Electric)	9802	117	10	128	NA
Hydrogen	3177	125		125	NA
Batteries	NA	NA	63	63	NA

Lifetime Costs estimation

Diesel Var.	Diesel const	Diesel-Battery	LNG Const	LNG-Battery	Batteries	Hydrogen
365	366	463	341	413	1346	670

Project	NA	
Ship name	NFT Steigen	D. SHIP DESIGN - Ferry

Power-speed Curve



Main Dimensions

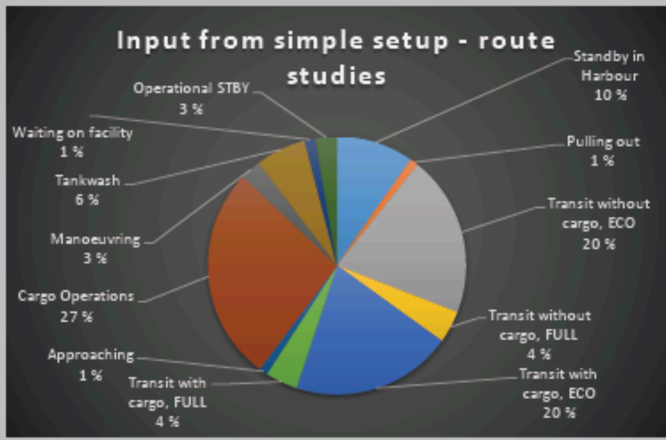
	L_{OA}	L_{PP}	L_{WL}	Breadth	Draught	Deadwgt.	Lightwgt	Ballast	Service Area
Dimensions	0	0	0	0	0	8000	0	0	1

Project	NA
Ship name	NFT Steigen

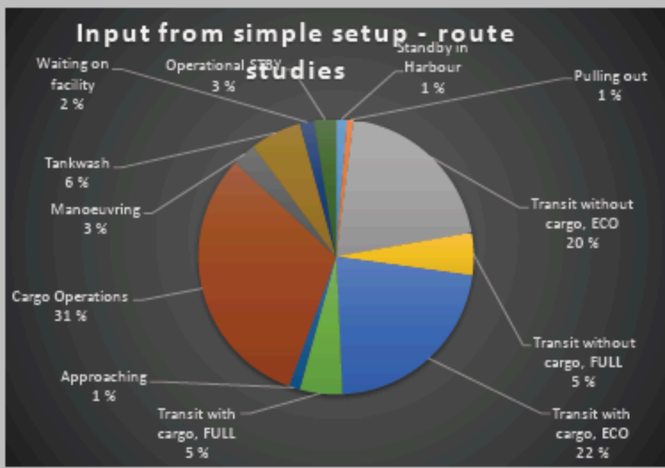
E. ROUTE STUDIES

Input from simple setup - route studies

	Hours per month	
Standby in Harbour	72	hours
Pulling out	8	hours
Transit without cargo, ECO	150	hours
Transit without cargo, FULL	30	hours
Transit with cargo, ECO	150	hours
Transit with cargo, FULL	30	hours
Approaching	8	hours
Cargo Operations	200	hours
Manoeuvring	19	hours
Tankwash	47	hours
Waiting on facility	10	hours
Operational STBY	20	hours



	kWh	
Standby in Harbour	20160	kWh
Pulling out	12000	kWh
Transit without cargo, ECO	315000	kWh
Transit without cargo, FULL	78000	kWh
Transit with cargo, ECO	345000	kWh
Transit with cargo, FULL	78000	kWh
Approaching	20800	kWh
Cargo Operations	490000	kWh
Manoeuvring	43700	kWh
Tankwash	94000	kWh
Waiting on facility	26000	kWh
Operational STBY	40000	kWh



Capabilites and Sea Margin

Capabilites	
Level	%
1	20
2	40
3	70
4	100

Sea Margin	
Level	%
1	5
2	12
3	18
4	40

Project	NA
Ship name	NFT Steigen

F. ENGINE SETUP

Efficiency, propulsion

	Diesel Var.	Diesel const	Diesel-Battery	LNG Const	LNG-Battery	Batteries	Hydrogen
Generator	no	no	yes	yes	yes	no	no
Drives/Converter	no	no	yes	yes	yes	yes	yes
Cabling	no	no	yes	yes	yes	yes	yes
Switchboard	no	no	yes	yes	yes	yes	yes
El-motors	no	no	yes	yes	yes	yes	yes
DC/DC converters	no	no	no	no	no	no	yes
Gear	yes	yes	yes	no	no	yes	yes
Overall	95,00 %	95,00 %	75,91 %	79,01 %	79,01 %	79,01 %	75,06 %

Efficiency, electricity production

	Diesel Var.	Diesel const	Diesel-Battery	LNG Const	LNG-Battery	Batteries	Hydrogen
Generator	yes	yes	yes	yes	yes	no	no
Drives/converter	yes	yes	yes	yes	yes	yes	yes
Cabling	yes	yes	yes	yes	yes	yes	yes
Switchboard	yes	yes	yes	yes	yes	yes	yes
DC/DC Converters	yes	no	yes	yes	yes	yes	yes
Open	yes	no	yes	yes	yes	yes	no
Overall	80,67 %	83,17 %	79,01 %	79,01 %	79,01 %	83,17 %	83,17 %

Efficiency, fossile fuels

	Const	x	x^2	x^3	x^4	x^5	x^6
Diesel Variable RPM	0,3099	0,58	-4,0844	15,441	-29,665	27,841	-10,15
Diesel Constant RPM	0,1667	1,1482	-3,1976	5,072	-4,1771	1,3626	
LNG	0,1406	0,01706	-0,0004	4,00E-06	-2,00E-08		

Efficiency, electricity production, Hydrogen

Max power	4440		Number of cells	37		54% until	1295	kW
Hours of operation	25000	h				Peak Power Efficiency	54 %	
Design lifetime	3,00	years	Weight	13320	kg	Peak Efficiency	35	kW
Design Stack Size	120	kW	Cost cells	57,35	MNOK			

From max efficiency to mac performance

const	x	x^2	x^3	x^4
0,44	0,84	-2,54	2,96	-1,25

Efficiency, electricity production, Batteries

Design lifetime	10	years	*Design Capacity*	68629,11	kWh
Cycluses	1,2		*Number of stacks*	506	Stacks
Allowed discharge	80	%	*Weight of stacks*	891774	kg

Power	34314,6	68629,11	102944	137258	171573	205887,334
Losses	0,95 %	1,75 %	2,55 %	3,50 %	4,30 %	5,25 %

Time in harbour for charging	60	min

Hybridization

Charging power	1400	kW	*Battery Lifetime*	10	years
Time for charging	60	min	*Battery % of kWh*	15,00 %	
Per day	1,2	n			

Carbon footprint and well to wheel efficiency fromproduction

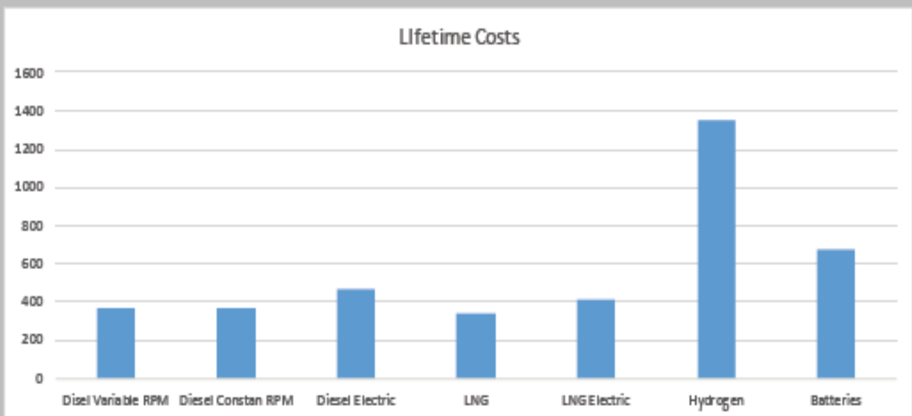
	CO2-equivalents	Well to wheel efficiency
	per kg fuel, g	%
Diesel variable rpm	*397,22*	
LNG	*407,84*	
Electricity, Norwegian mix	50	

Project	17-144	
Ship name	NFT Steigen	

G. COST AND ASSEMBLY

Price development and investments

	Disel Variable RPM		Diesel Constan RPM		Diesel Electric		LNG		LNG Electric		Hydrogen		Batteries	
	CAPEX	OPEX	CAPEX	OPEX	CAPEX	OPEX	CAPEX	OPEX	CAPEX	OPEX	CAPEX	OPEX	CAPEX	OPEX
1	13,0	33,30	13,0	33,45	71,7	34,79	43,3	28,37	100,6	27,51	57,4	106,16	374,7	13,41
2	0	33,30	0	33,45	0	34,79	0	28,37	0	27,51	0	106,16	0	13,41
3	0	33,30	0	33,45	0	34,79	0	28,37	0	27,51	0	106,16	0	13,41
4	0	33,30	0	33,45	0	34,79	0	28,37	0	27,51	57,35	106,16	0	13,41
5	0	33,30	0	33,45	0	34,79	0	28,37	0	27,51	0	106,16	0	13,41
6	0	33,30	0	33,45	0	34,79	0	28,37	0	27,51	0	106,16	0	13,41
7	0	33,30	0	33,45	0	34,79	0	28,37	0	27,51	57,35	106,16	0	13,41
8	0	33,30	0	33,45	0	34,79	0	28,37	0	27,51	0	106,16	0	13,41
9	0	33,30	0	33,45	0	34,79	0	28,37	0	27,51	0	106,16	0	13,41
10	0	33,30	0	33,45	0	34,79	0	28,37	0	27,51	57,35	106,16	0	13,41
11	0	33,30	0	33,45	58,74694	34,79	0	28,37	57,3054	27,51	0	106,16	374,715	13,41
12	0	33,30	0	33,45	0	34,79	0	28,37	0	27,51	0	106,16	0	13,41
13	0	33,30	0	33,45	0	34,79	0	28,37	0	27,51	57,35	106,16	0	13,41
14	0	33,30	0	33,45	0	34,79	0	28,37	0	27,51	0	106,16	0	13,41
15	0	33,30	0	33,45	0	34,79	0	28,37	0	27,51	0	106,16	0	13,41
16	0	33,30	0	33,45	0	34,79	0	28,37	0	27,51	57,35	106,16	0	13,41
17	0	33,30	0	33,45	0	34,79	0	28,37	0	27,51	0	106,16	0	13,41
18	0	33,30	0	33,45	0	34,79	0	28,37	0	27,51	0	106,16	0	13,41
19	0	33,30	0	33,45	0	34,79	0	28,37	0	27,51	57,35	106,16	0	13,41
20	0	33,30	0	33,45	0	34,79	0	28,37	0	27,51	0	106,16	0	13,41
Costs		364,914		366,479		463,4931		341,073		412,766		1345,92		670,332



	Average price	NOK		NOK		MNOK		NOK
MGO	Price per kWh	0,58	Price per kW	3000	Lifetime	20	Maintenance per year per kW	0
LNG	Price per kWh	0,58	Price per kW	10000	Lifetime	20	Maintenance per year per kW	0
Hydrogen	Price per kWh	2,28	Price per kW	13000	Lifetime	3,00	Maintenance per year per kW	0
Batteries	Price per kWh	0,57	Price per kWh	5460	Lifetime	10,00	Maintenance per year per kWh	0

Interest 7 %

D. Instruction Manual

Instruction Manual

For “The Tool”

Author:

Jørgen Kopperstad

A Part of a Master´s Thesis in Renewable Energy

University of Bergen

Geophysical Institute

May 21, 2018

Instruction Manual for “The Tool”

Jørgen Kopperstad

http://bora.uib.no/

Preface

This instruction manual is written to present how to use “The Tool”. It is an attachment to the master´s thesis in Renewable Energy made by the student Jørgen Kopperstad. “The Tool” is a numerical approach to ship energy analysis and are designed to be used for early stage analysis in ship design processes to show upsides, downsides, challenges and opportunities with diesel, LNG, Hydrogen and battery-technology for powertrains.

Content

1. Introduction

The interface of the tool is based on eight sheets as shown in Figure 1. The first sheet is the front-sheet. Here, useful information describes which ship that are analyzed, what date the report is made and etc.

Sheet B1 and B2 are only for inputs. Sheet B1 are used if the user only uses simple inputs and sheet B2 are for more advanced inputs.

Sheet C presents the summarized results and sheet D-G are the ship design, route studies, engine setup and costs setup.

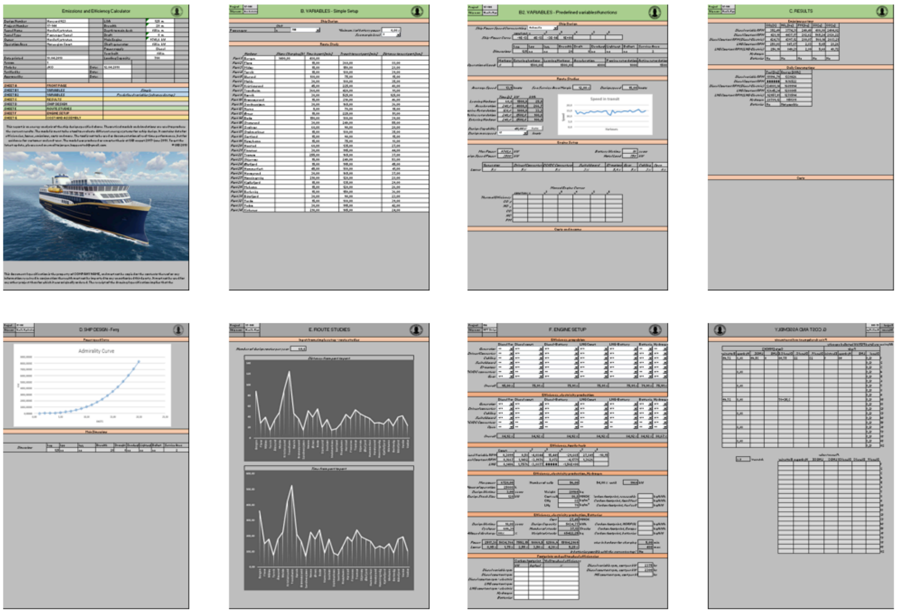


Figure 1 Interface of the tool.

The different cells in the tool have different colors as shown in Table 1. In general, all input-cells with a white color represent necessary inputs or simple inputs. These always have to be filled in. The light-grey cells represent predefined inputs. These are not necessary to edit but can be changed if the user find it useful. The dark-grey cells are results, text or indicators. These are not to be changed.

Table 1 Color coding of necessary inputs, predefined inputs and results, text or indicators.

Necessary inputs	Predefined inputs	Results, text or indicators

The last sheet in the tool is the data sheet. This is recommended not to edit unless the user knows how to and has a specific purpose by doing this. Setting and modifications are described further in section 4.

2. Simple inputs

The simple inputs of the tool are based on route studies and the most necessary ship design inputs. When using this setup, it is important to always take into consideration the predefined variables which are the basis for the calculations made.

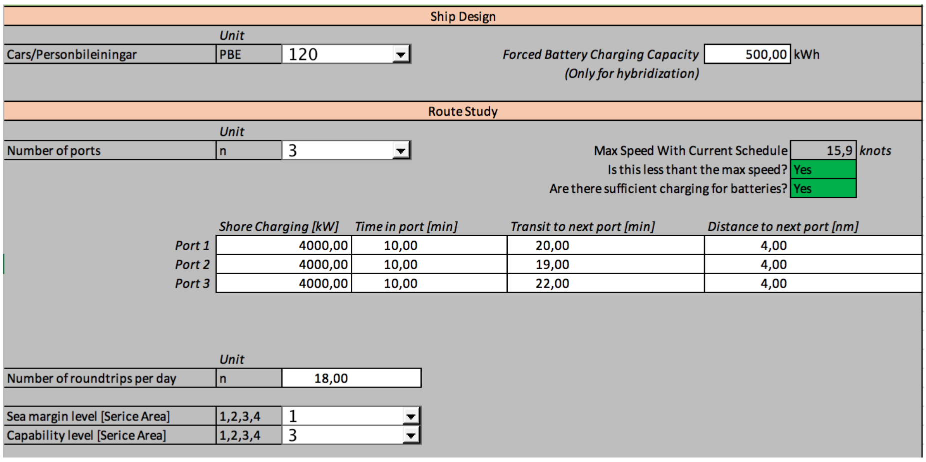
2.1 Double ended Car Ferry

When the tool is opened, go to “file” and “save as” and set a filename to make a copy of the tool. By doing this, you can always go back to the original version if you run into bugs or need to begin all over again.

The simple input procedure is listed underneath, and a screenshot can be found in Figure 2.

I. Choose the size of the ferry that you want to analyze.
II. If you want to limit the size of the battery, set the “Forced Battery Charging capacity” to a value of your own choice. If this value is set to 0, the battery size will be suited to the maximum charging capacity available from shore.
III. Select the numbers of ports that the ferry is operating/going to operate.
IV. Select shore charging capacity. This is available shore connection. Hotel Power will be subtracted from this automatically. Also select time in port, transit to next port and distance from port to port.
V. Select the numbers of routes sailed per day.
VI. Select sea margin level based on operation area — Suggested value: 2
VII. Select Capability level based on operation area. — Suggested value: 2
VIII. Read results.

Note: Whenever changing the settings, make sure that “is this less than the max speed” and “are there sufficient charging for batteries” (If Batteries are considered) are indicating “Yes”.



Ship Design

	Unit			
Cars/Personbileiningar	PBE	120	*Forced Battery Charging Capacity (Only for hybridization)*	500,00 kWh

Route Study

	Unit			
Number of ports	n	3	Max Speed With Current Schedule	15,9 *knots*
			Is this less thant the max speed?	Yes
			Are there sufficient charging for batteries?	Yes

	Shore Charging [kW]	*Time in port [min]*	*Transit to next port [min]*	*Distance to next port [nm]*
Port 1	4000,00	10,00	20,00	4,00
Port 2	4000,00	10,00	19,00	4,00
Port 3	4000,00	10,00	22,00	4,00

	Unit	
Number of roundtrips per day	n	18,00
Sea margin level [Serice Area]	1,2,3,4	1
Capability level [Serice Area]	1,2,3,4	3

Figure 2 Simple setups for double ended car ferries.

2.2 Life Fish Carrier

When the tool is opened, go to "file" and "save as" to make a copy of the tool. By doing this, you can always go back to the original version if you run into bugs or need to begin all over again.

The simple inputs procedure are listed underneath and a screenshot can be found in Figure 3.

I. Choose the size of the water capacity of the live fish carrier you want to analyze.
II. If you want to select the minimum % of energy consumed from batteries for hybrid solutions, you *can* select this in "Minimum % of battery power".
III. Select the hours used per month for the different operations. The indicators "hours per month" and "left" are there to make sure that you have entered enough hours for one month (31 days), "left" should always indicate "0".
IV. Select sea margin level based on operation area. Suggested value: 2
V. Select Capability level based on operation area. Suggested value: 2
VI. Select the design route option if you also want to consider powertrains with only batteries for this study. In the design route a specific route that the capacity of the battery has to be designed for has to be specified.
VII. Read results.

Ship Design

	Unit		
Water	m^3	3250	
Minimum % of battery power		15,00 %	

Route Study

	Hours per month	*31 days*
Standby in Harbour	72	*hours*
Pulling out	8	*hours*
Transit without cargo, ECO	150	*hours*
Transit without cargo, FULL	30	*hours*
Transit with cargo, ECO	150	*hours*
Transit with cargo, FULL	30	*hours*
Approaching	8	*hours*
Cargo Operations	200	*hours*
Manoeuvring	19	*hours*
Tankwash	47	*hours*
Waiting on facility	10	*hours*
Operational STBY	20	*hours*
Hours per month	744	
Left	0	

Capability level	2
Sea margin level	1

Design route (Optional)

Pulling out	5	*min*
Transit without cargo, ECO	300	*min*
Transit without cargo, FULL		*min*
Transit with cargo, ECO	600	*min*
Transit with cargo, FULL		*min*
Approaching	20	*min*
Cargo Operations	120	*min*
Manoeuvring	40	*min*
Tankwash	60	*min*
Waiting on facility	30	*min*
Operational STBY		*min*

Figure 3 Simple setups for Live Fish Carriers.

2.3 Passenger Vessel

When the tool is opened, go to "file" and "save as" to make a copy of the tool. By doing this, you can always go back to the original version if you run into bugs or need to begin all over again.

The simple inputs procedure are listed underneath and a screenshot can be found in Figure 4.

I. Choose the passenger capacity that you want to analyze.
II. If you want to limit the size of the battery, set the "Max Battery Capacity" to a value of your own choice. If this value is set to 0, the battery size will be suited to the maximum charging capacity available from shore.
III. Select name of port, time in port, transit to this port [min] and Distance to this port.
IV. Select shore charging capacity. This is available shore connection. Hotel Power will be subtracted from this automatically. Also select time in port, transit to next port and distance from port to port.
V. Select sea margin level based on operation area — Suggested value: 2
VI. Select Capability level based on operation area. — Suggested value: 2
VII. Read results.

Ship Design				
	Unit			
Passengers	n	700	*Max Battery Size*	kWh
			Sea margin level	2
			Capability level	1

Route Study	*Harbour*	*Shore Charging [kW]*	*Time in port [min]*	*Transit to this port [min]*	*Distance to this port [nm]*
Port 1	Bergen	1400,00	480,00		
Port 2	Florø		15,00	360,00	88,00
Port 3	Måløy		15,00	150,00	28,00
Port 4	Torvik		15,00	180,00	39,00
Port 5	Ålesund		180,00	75,00	15,00
Port 6	Molde		30,00	180,00	35,00
Port 7	Kristiansund		45,00	225,00	48,00
Port 8	Trondheim	1400,00	360,00	420,00	91,00
Port 9	Rørvik		30,00	525,00	125,00
Port 10	Brønnøysund		15,00	210,00	46,00
Port 11	Sandnessjøen		30,00	165,00	36,00
Port 12	Nesna		5,00	70,00	15,00
Port 13	Ørnes		15,00	225,00	51,00
Port 14	Bodø	1400,00	150,00	180,00	39,00
Port 15	Stamsund		30,00	240,00	55,00
Port 16	Svolvær		60,00	90,00	20,00
Port 17	Stokmarknes		15,00	180,00	35,00
Port 18	Sortland		15,00	90,00	15,00
Port 19	Risøyhamn		15,00	75,00	18,00
Port 20	Harstad		60,00	135,00	27,00
Port 21	Finnsnes		30,00	195,00	44,00
Port 22	Tromsø	1400,00	255,00	165,00	37,00
Port 23	Skjervøy		15,00	240,00	53,00
Port 24	Øksfjord		15,00	195,00	45,00
Port 25	Hammerfest		45,00	180,00	41,00
Port 26	Havøysund		30,00	165,00	37,00
Port 27	Honningsvåg	1400,00	210,00	120,00	28,00
Port 28	Kjøllefjord		15,00	135,00	29,00
Port 29	Mehamn		15,00	120,00	26,00
Port 30	Berlevåg		15,00	150,00	36,00
Port 31	Båtsfjord		30,00	90,00	23,00
Port 32	Vardø		15,00	180,00	39,00
Port 33	Vadsø		30,00	195,00	42,00
Port 34	Kirkenes		210,00	105,00	24,00

Figure 4 Simple setups for the passenger vessel.

3. Advanced inputs

The advanced inputs are there for users who have sufficient information of the design studied so that they can edit the predefined inputs and hence achieving a more accurate result.

The advanced inputs always start by the simple inputs. Therefore, read 2.1-2.3 and follow the instruction before starting to use advanced inputs.

3.1 Double ended car ferry

The first advanced setups for the car ferry version of the tool are described underneath. All of them are predefined so that the user can edit them if wanted.

3.1.1 Ship Design

In Sheet B2 the ship design input can be found as in Figure 5. In sheet D the admiralty curve is illustrated graphically, and the main dimensions are listed as shown in Figure 6.

a) The power-speed curve setting can be changed from “Automatic” to “Manual”. Then the values for the power-speed curve will have to be added manually. The power-speed curve can also be changed without switching from “Automatic” to “Manual” by editing “design-speed” and “design-speed-power” in sheet B2. By doing this, the admiralty method is used to estimate a power-speed curve.
b) Dimensions can be added. If deadweight and lightweight are added, the additional resistance by use of batteries are added to the power-speed curve by use of the admiralty method.
c) Operational loads can be changed if wanted. If the ferry is not connected to shore during loading this can be changed in “Connected to Shore” by writing “no”.

Ship Design

			constant	x	x^2	x^3
Ship Power Speed Curve Setting	Automatic	*Ship-Power Curve*	8E-01	0E+00	8E-01	8,5E-01

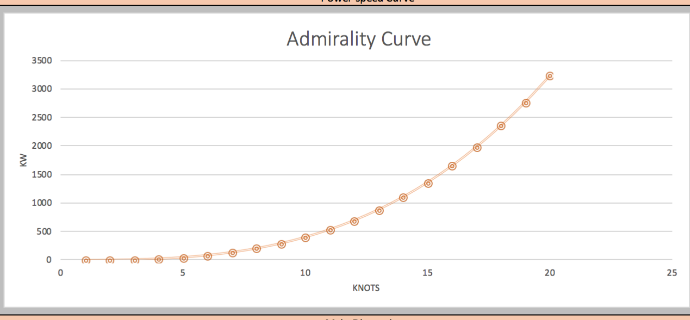
	L_{OA}	L_{PP}	L_{WL}	Breadth	Draft	Deadwgt.	Lightwgt	Ballast	Service Area
Dimensions	125	na	na	20	0	na	na	na	1

	Loading	Entering harbour	Leaving Harbour	Acceleration	Passive retardation	Active retardation
Operational Loads	0	350,00	250,00	700	55	200
Connected to shore	*yes*					

Figure 5 Ship Design inputs in Sheet B2.

None of the information found in Figure 6 is editable. The purpose of sheet D is to show the power-speed curve and the main particulars for the reader of the report.

Power-speed Curve



Main Dimensions

	L_{OA}	L_{PP}	L_{WL}	Breadth	Draught	Deadwgt.	Lightwgt	Ballast	Service Area
Dimensions	125	na	na	20	0	na	na	na	1

Figure 6 In Sheet D the Admiralty Curve is graphically presented and the main dimensions are listed.

3.1.2 Route Studies

In Sheet B2 the route study inputs can be found (Figure 7). In sheet D the Route Presentations and editable values for capability and sea margins are found (Figure 8).

a) If wanted, the capability level and Sea Service Area Margin can be edited. It is recommended that these are changed by selecting level in sheet B1 instead of writing a number in sheet B2. The multiplication factor for the level can again be changed in Sheet E shown in Figure 8.
b) The use can edit the time necessary for loading, entering harbor, leaving harbor, acceleration, passive retardation and active retardation. This have to be specified as a function per harbor.
c) Design-speed is described in section 3.1.1.
d) Distance for maneuvering can be edited. This is the same distance used for all harbors.
e) Max speed can be edited. This is used to estimate necessary engine size.

Route Studies

Capability	70,00 %	*Sea Service Area Margin*	5,00 %	*Minutes in port*	258
				Minutes at sea	1182

Time in different ports [s]

	Shore	Loading	Entering harbour	Leaving Harbour	Acceleration	Passive retardation	Active retardation
Port 1		*600*	90	30	124,00	120	30
Port 2		*600*	90	30	124,00	120	30
Port 3		*600*	90	30	124,00	120	30

Design speed	12,00	knots	*Distance for maneuvring*	*0,7*	*nm*	*Max Speed*	*16* *knots*

Figure 7 Route Studies Advanced inputs found in Sheet B2.

“Minutes in port” and “Minutes at sea” are just indicators.

The purpose of the graphical illustration of route studies in sheet E (shown in figure Figure 8) is to illustrate what the ship is being used for, and which modes that are using most energy.

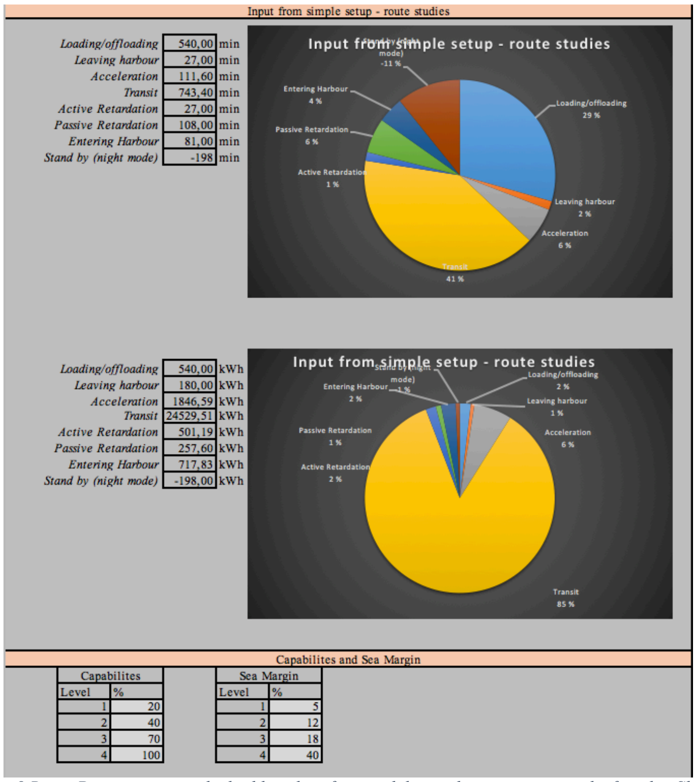


Figure 8 Route Presentations and editable values for capability and sea margins can be found in Sheet E.

3.1.3 Engine Setup

In Sheet B2 the engine setup can be found as in Figure 9. In sheet E, more settings for engine configurations can be found. Sheet E is presented in Figure 10.

Figure 9:

a) Design Speed Power are described in section 3.1.1.
b) Max Power is the calculated maximum power necessary to run the ship. This is predefined and is recommended not changed unless the user has a specific value to use.
c) Hotel power is set to 60 kW but is editable if wanted.
d) Component losses can be edited.
e) If the user wants to add one component that is not included in the tool, “Open” can be changed. The representative component loss has to be added. It also has to be activated in sheet F to be used.
f) Emission-factors can be edited.

Engine Setup

Max Power	2820,7	kW	Hotel Power 60 kW
Design Speed Power	700	kW	

	Generator	Drives/Converter	DC/DC Converters	Switchboard	El-motors	Gear	Cabling	Open
Losses	5 %	5 %	5 %	3 %	5,9 %	5 %	3 %	0 %

Emissions

	CO_2 per kg fuel, kg	Nox per kWh, g	CO per kWh, g	PM per kWh, g	SO per kWh, g
Diesel Variable RPM	3,17	7,85	5	0,5	1
Diesel Constant RPM	3,17	7,85	5	0,5	1
LNG Constant RPM	2,76	1,5	0,05	0,005	0,01

Figure 9 Engine Setup in Sheet B1.

Figure 10:

g) Efficiency losses for propulsion and electricity can be activated or deactivated. Indicators underneath shows the representative efficiency of the powertrain (excluding the engine).
h) Manual Engine load-curves can be added for fossil fuel engines under “Efficiency, Fossil fuels”.
i) The expected lifetime of a fuel cell can be changed in “Hours of operation”.
j) The design stack power can be edited under “Design Stack Size”.
k) The Peak power efficiency can be edited. This is the power that the stack delivers when it is running at peak efficiency.
l) The peak efficiency can be edited.
m) The efficiency curve describing the efficiency from peak and forward can be edited.
n) The design lifetime of batteries can be edited.
o) The losses related to the power listed can be edited.
p) The carbon footprint by production, transport and storage of LNG, Diesel and electricity (Norwegian mix) can be edited.
q) The well-to-wheel efficiency can be added.

Efficiency, propulsion

	Diesel Var	Diesel const	Diesel-Battery	LNG Const	LNG-Battery	Batteries	Hydrogen
Generator	no	no	yes	yes	yes	no	no
Drives/Converter	no	no	yes	yes	yes	yes	yes
Cabling	no	no	yes	yes	yes	yes	yes
Switchboard	no	no	yes	yes	yes	yes	yes
El-motors	no	no	yes	yes	yes	yes	yes
DC/DC converters	no	no	no	no	no	no	yes
Gear	yes	yes	yes	no	no	yes	yes
Overall	95,00 %	95,00 %	75,91 %	79,91 %	79,91 %	79,91 %	75,91 %

Efficiency, electricity production

	Diesel Var	Diesel const	Diesel-Battery	LNG Const	LNG-Battery	Batteries	Hydrogen
Generator	yes	yes	yes	yes	yes	no	no
Drives/converter	yes	yes	yes	yes	yes	yes	yes
Cabling	yes	yes	yes	yes	yes	yes	yes
Switchboard	yes	yes	yes	yes	yes	yes	yes
DC/DC Converters	no	no	yes	yes	yes	yes	yes
Open	no	no	yes	yes	yes	yes	no
Overall	84,92 %	84,92 %	80,67 %	80,67 %	80,67 %	84,92 %	84,92 %

Efficiency, fossile fuels

	Const	x	x^2	x^3	x^4	x^5	x^6
iesel Variable RPM	0,3099	0,58	-4,0844	15,441	-29,665	27,841	-10,15
esel Constant RPM	0,1667	1,1482	-3,1976	5,072	-4,1771	1,3626	
LNG	0,1406	1,7576	-3,8877	#######	-1,56E+00		

Efficiency, electricity production, Hydrogen

Max power	1746,59		Number of cells	15,00		54% until	525	kW
Hours of operation	25000	h				ak Power efficiency	35	kW
Design lifetime	3,00	years	Weight	5400	kg	Peak Efficiency	54 %	
Design Stack Size	120	kW	Cost cells	23,25	MNOK			

From max efficiency to mac performance

const	x	x^2	x^3	x^4
0,44	0,84	-2,54	2,96	-1,25

Efficiency, electricity production, Batteries

Design lifetime	10	years	*Design Capacity*	3357,01	kWh
Cycluses	19710		*Number of stacks*	24,76	Stacks
Allowed discharge	40	%	*Weight of stacks*	43621,34	kg

Power	1678,51	3357,011	5035,52	6714,02	8392,53	10071,034
Losses	0,95 %	1,75 %	2,55 %	3,50 %	4,30 %	5,25 %

Carbon footprint and well to wheel efficiency fromproduction

	CO2-equivalents	Well to wheel efficiency
	per kg fuel, g	%
Diesel variable rpm	*397,22*	
LNG	*407,84*	
Electricity, Norwegian mix	50	

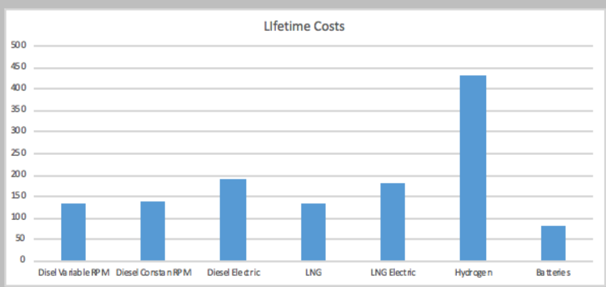
Figure 10 Sheet E - Engine Setup.

3.1.4 Costs

In Sheet B2 the cost setup can be found as in Figure 11.

a) The cost of fuels per kWh can be edited.
b) The installation cost per kW for the specific engine type can be edited.
c) The expected lifetime of the system can be edited.
d) The maintenance cost per kW per year can be edited.
e) The interest rate can be edited.

Price development and investments														
	Disel Variable RPM		Diesel Constan RPM		Diesel Electric		LNG		LNG Electric		Hydrogen		Batteries	
	CAPEX	OPEX	CAPEX	OPEX	CAPEX	OPEX	CAPEX	OPEX	CAPEX	OPEX	CAPEX	OPEX	CAPEX	OPEX
1	8,5	12,02	8,5	12,55	12,56	16,58	28,21	10,19	35,03	13,89	29,53	31,39	18,33	5,10
2	0	12,02	0	12,55	0,00	16,58	0,00	10,19	0,00	13,89	0,00	31,39	0,00	5,10
3	0	12,02	0	12,55	0,00	16,58	0,00	10,19	0,00	13,89	0,00	31,39	0,00	5,10
4	0	12,02	0	12,55	0,00	16,58	0,00	10,19	0,00	13,89	22,71	31,39	0,00	5,10
5	0	12,02	0	12,55	0,00	16,58	0,00	10,19	0,00	13,89	0,00	31,39	0,00	5,10
6	0	12,02	0	12,55	0,00	16,58	0,00	10,19	0,00	13,89	0,00	31,39	0,00	5,10
7	0	12,02	0	12,55	0,00	16,58	0,00	10,19	0,00	13,89	22,71	31,39	0,00	5,10
8	0	12,02	0	12,55	0,00	16,58	0,00	10,19	0,00	13,89	0,00	31,39	0,00	5,10
9	0	12,02	0	12,55	0,00	16,58	0,00	10,19	0,00	13,89	0,00	31,39	0,00	5,10
10	0	12,02	0	12,55	0,00	16,58	0,00	10,19	0,00	13,89	22,71	31,39	0,00	5,10
11	0	12,02	0	12,55	4,10	16,58	0,00	10,19	6,83	13,89	6,83	31,39	18,33	5,10
12	0	12,02	0	12,55	0,00	16,58	0,00	10,19	0,00	13,89	0,00	31,39	0,00	5,10
13	0	12,02	0	12,55	0,00	16,58	0,00	10,19	0,00	13,89	22,71	31,39	0,00	5,10
14	0	12,02	0	12,55	0,00	16,58	0,00	10,19	0,00	13,89	0,00	31,39	0,00	5,10
15	0	12,02	0	12,55	0,00	16,58	0,00	10,19	0,00	13,89	0,00	31,39	0,00	5,10
16	0	12,02	0	12,55	0,00	16,58	0,00	10,19	0,00	13,89	22,71	31,39	0,00	5,10
17	0	12,02	0	12,55	0,00	16,58	0,00	10,19	0,00	13,89	0,00	31,39	0,00	5,10
18	0	12,02	0	12,55	0,00	16,58	0,00	10,19	0,00	13,89	0,00	31,39	0,00	5,10
19	0	12,02	0	12,55	0,00	16,58	0,00	10,19	0,00	13,89	22,71	31,39	0,00	5,10
20	0	12,02	0	12,55	0,00	16,58	0,00	10,19	0,00	13,89	0,00	31,39	0,00	5,10
Costs	135,2		140,862		189,3154		134,318		183,147		429,751		79,9034	



	Average price	NOK		NOK		MNOK		NOK
MGO	Price per kWh	0,58	Price per kW	3000	Lifetime	20	Maintenance per year per kW	0
LNG	Price per kWh	0,58	Price per kW	10000	Lifetime	20	Maintenance per year per kW	0
Hydrogen	Price per kWh	2,28	Price per kW	13000	Lifetime	3,00	Maintenance per year per kW	0
Batteries	Price per kWh	0,57	Price per kWh	5460	Lifetime	10,00	Maintenance per year per kWh	0

Interest	7 %

Figure 11 Cost Setups in Sheet G.

3.2 Live Fish Carrier

The first advanced setups are ship design. Then Route studies and engine setup. In the end, costs can be edited.

3.2.1 Ship Design

In Sheet B2 the ship design input can be found as in Figure 12. In sheet D the admiralty curve is illustrated graphically, and the main dimensions are listed as shown in Figure 13.

a) If wanted, the power-speed curve setting can be changed from “Automatic” to “Manual”. Then the values for the power-speed curve will have to be added manually. The power-speed curve can also be changed by editing “design-speed” and “design-speed-power” in sheet B2. By doing this, the admiralty method is used to estimate a power-speed curve.
b) Dimensions can be added. If deadweight and lightweight are added, the additional resistance by use of batteries are added to the power-speed curve.
c) Operational loads can be changed if wanted.

Ship Design

			constant	x	x^2	x^3
Ship Power Speed Curve Setting	Automatic	*Ship-Power Curve*	8E-01	0E+00	8E-01	8,3E-01

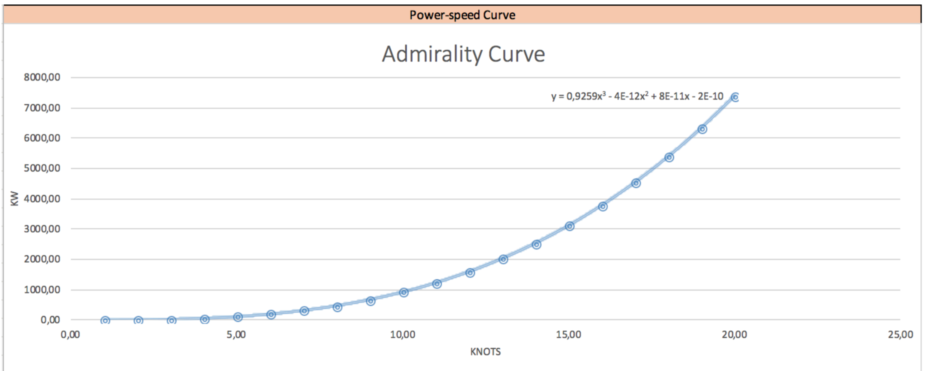
	L_{OA}	L_{PP}	L_{WL}	Breadth	Draught	Deadwgt.	Lightwgt	Ballast	Service Area
Dimensions						8000			1

Operation Power [kW]

Standby in Harbour	280	Transit with cargo, ECO	2000	Manoeuvring	2300
Pulling out	1500	Transit with cargo, FULL	2600	Tankwash	1000
Transit without cargo, ECO	1500	Approaching	2000	Waiting on facility	1000
Transit without cargo, FULL	2300	Cargo Operations	2450	Operational STBY	1000

Figure 12 Ship Design inputs in Sheet B2.

Power-speed Curve



Main Dimensions

	L_{OA}	L_{PP}	L_{WL}	Breadth	Draught	Deadwgt.	Lightwgt	Ballast	Service Area
Dimensions	0	0	0	0	0	8000	0	0	1

Figure 13 In Sheet D the Admiralty Curve is graphically presented and the main dimensions are listed.

3.2.2 Route Studies

In Sheet B2 the route study inputs can be found as in Figure 14. In sheet D the Route Presentations and editable values for capability and sea margins are found as in Figure 15.

a) If wanted, the capability level and Sea Service Area Margin can be edited. It is recommended that these are changed by selecting level in sheet B1 instead of writing a number in sheet B2. The multiplication factor for the level picked can again be changed in Sheet E as shown in Figure 15.
b) Design-speed is described in section 3.1.1.

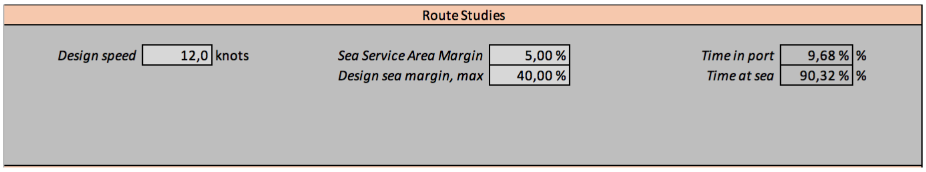


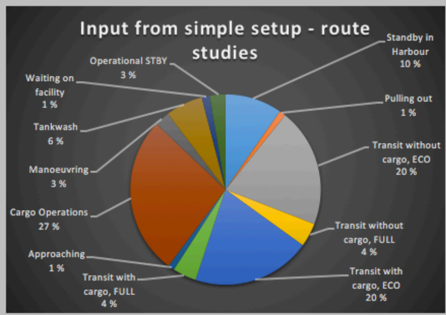
Figure 14 Route Studies Advanced inputs found in Sheet B2.

“Time in port” and “Time at sea” are just indicators.

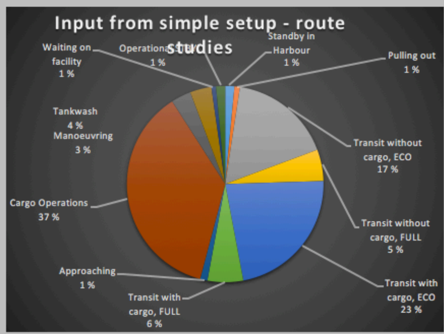
The purpose of the graphical illustration of route studies in sheet E (shown in figure Figure 15) is to illustrate what the ship is being used for, and which modes that are using most energy.

Input from simple setup - route studies

	Hours per month	
Standby in Harbour	72	*hours*
Pulling out	8	*hours*
Transit without cargo, ECO	150	*hours*
Transit without cargo, FULL	30	*hours*
Transit with cargo, ECO	150	*hours*
Transit with cargo, FULL	30	*hours*
Approaching	8	*hours*
Cargo Operations	200	*hours*
Manoeuvring	19	*hours*
Tankwash	47	*hours*
Waiting on facility	10	*hours*
Operational STBY	20	*hours*



	kWh	
Standby in Harbour	20160	*kWh*
Pulling out	12000	*kWh*
Transit without cargo, ECO	225000	*kWh*
Transit without cargo, FULL	69000	*kWh*
Transit with cargo, ECO	300000	*kWh*
Transit with cargo, FULL	78000	*kWh*
Approaching	16000	*kWh*
Cargo Operations	490000	*kWh*
Manoeuvring	43700	*kWh*
Tankwash	47000	*kWh*
Waiting on facility	10000	*kWh*
Operational STBY	20000	*kWh*



Capabilites and Sea Margin

Capabilites	
Level	%
1	20
2	40
3	70
4	100

Sea Margin	
Level	%
1	5
2	12
3	18
4	40

Figure 15 Route Presentations and editable values for capability and sea margins can be found in Sheet E.

3.2.3 Engine Setup

In Sheet B2 the engine setup can be found as in Figure 16. In sheet E, more settings for engine configurations can be found. Sheet E is presented in Figure 17.

Figure 16:

a) Design Speed Power are described in section 3.1.1.
b) Max Power is the calculated maximum power necessary to run the ship. This is predefined and is recommended not changed unless the user has a specific value to use.
c) Hotel power is set to 100 kW but is editable if wanted.
d) Component losses can be edited.
e) If the user wants to add one component that is not included in the tool, "Open" can be changed. The representative component loss has to be added.

f) The “Power Only for propulsion”-input defines how much of the energy that is used for propulsion for the different operations. The different operations are described in “Ship Design”.
g) Emission-factors can be edited.

Engine Setup

Max Power	4333,3	kW
Design Speed Power	1600	kW
Hotel Load	100	kW

	Generator	Drives/Converter	DC/DC Converters	Switchboard	El-motors	Gear	Cabling	Open
Losses	5 %	5 %	5 %	3 %	5,9 %	5 %	3 %	0 %

Power only for propulsion

Standby in Harbour	0	Transit with cargo, ECO	1700	Manoeuvring	1200
Pulling out	1300	Transit with cargo, FULL	2500	Tankwash	300
Transit without cargo, ECO	1100	Approaching	1700	Waiting on facility	400
Transit without cargo, FULL	2000	Cargo Operations	0	Operational STBY	400

Emissions

	CO_2 per kg fuel, kg	Nox per kWh, g	CO per kWh, g	PM per kWh, g	SO per kWh, g
Diesel Variable RPM	3,17	7,85	5	0,5	1
Diesel Constant RPM	3,17	7,85	5	0,5	1
LNG Constant RPM	2,76	1,5	0,05	0,005	0,01

Figure 16 Engine Setup in Sheet B1.

Figure 17:

a) Efficiency losses for propulsion and electricity can be activated or deactivated. Indicators underneath shows the representative efficiency of the powertrain (excluding the engine).
b) Manual Engine load-curves can be added for fossil fuel engines under “Efficiency, Fossil fuels”.
c) The expected lifetime of a fuel cell can be changed in “Hours of operation”.
d) The design stack power can be edited under “Design Stack Size”.
e) The Peak power efficiency can be edited. This is the power that the stack delivers when it is running at peak efficiency.
f) The peak efficiency can be edited.

g) The efficiency curve describing the efficiency from peak and forward can be edited.
h) The design lifetime of batteries can be edited.
i) The assumed charging power given that the ship is going to operate by a plug-in hybrid system is editable.
j) The assumed time for charging is editable.
k) The number of “design-routes” per day is editable.
l) The design lifetime of the batteries in hybrid systems is editable.
m) The % of energy that are supplied by batteries are editable.
n) The losses related to the power listed can be edited.
o) The carbon footprint by production, transport and storage of LNG, Diesel and electricity (Norwegian mix) can be edited.
p) The well-to-wheel efficiency can be added.

Efficiency, propulsion

	Diesel Var	Diesel const	Diesel-Battery	LNG Const	LNG-Battery	Batteries	Hydrogen
Generator	no	no	yes	yes	yes	no	no
Drives/Converter	no	no	yes	yes	yes	yes	yes
Cabling	no	no	yes	yes	yes	yes	yes
Switchboard	no	no	yes	yes	yes	yes	yes
El-motors	no	no	yes	yes	yes	yes	yes
DC/DC converters	no	no	no	no	no	no	yes
Gear	yes	yes	yes	no	no	yes	yes
Overall	95,00 %	95,00 %	75,91 %	79,01 %	79,01 %	79,01 %	75,06 %

Efficiency, electricity production

	Diesel Var	Diesel const	Diesel-Battery	LNG Const	LNG-Battery	Batteries	Hydrogen
Generator	yes	yes	yes	yes	yes	no	no
Drives/converter	yes	yes	yes	yes	yes	yes	yes
Cabling	yes	yes	yes	yes	yes	yes	yes
Switchboard	yes	yes	yes	yes	yes	yes	yes
DC/DC Converters	yes	no	yes	yes	yes	yes	yes
Open	yes	no	yes	yes	yes	yes	no
Overall	80,67 %	83,17 %	79,01 %	79,01 %	79,01 %	83,17 %	83,17 %

Efficiency, fossile fuels

	Const	x	x^2	x^3	x^4	x^5	x^6
iesel Variable RPM	0,3099	0,58	-4,0844	15,441	-29,665	27,841	-10,15
esel Constant RPM	0,1667	1,1482	-3,1976	5,072	-4,1771	1,3626	
LNG	0,1406	0,01706	-0,0004	4,00E-06	-2,00E-08		

Efficiency, electricity production, Hydrogen

Max power	4440		Number of cells	37		54% until	1295	kW
Hours of operation	25000	h				ık Power Efficiency	54 %	
Design lifetime	3,00	years	Weight	13320	kg	Peak Efficiency	35	kW
Design Stack Size	120	kW	Cost cells	57,35	MNOK			

From max efficiency to mac performance

const	x	x^2	x^3	x^4
0,44	0,84	-2,54	2,96	-1,25

Efficiency, electricity production, Batteries

Design lifetime	10	years	*Design Capacity*	56383,38	kWh
Cycluses	1,2		*Number of stacks*	416	Stacks
Allowed discharge	80	%	*Weight of stacks*	732651	kg

Power	28191,7	56383,38	84575,1	112767	140958	169150,133
Losses	0,95 %	1,75 %	2,55 %	3,50 %	4,30 %	5,25 %

Time in harbour for charging 60 min

Hybridization

Charging power	1400	kW	*Battery Lifetime*	10	years
Time for charging	60	min	*Battery % of kWh*	15,00 %	
Per day	1,2	n			

Carbon footprint and well to wheel efficiency fromproduction

	CO2-equivalents	Well to wheel efficiency
	per kg fuel, g	%
Diesel variable rpm	*397,22*	
LNG	*407,84*	
Electricity, Norwegian mix	50	

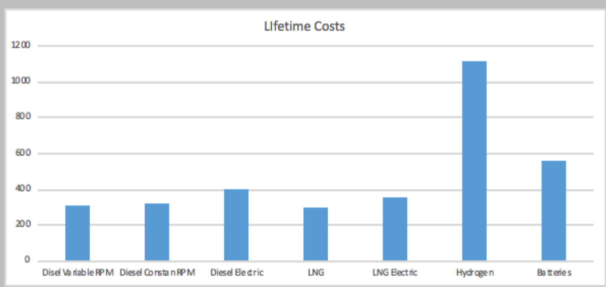
Figure 17 Sheet E - Engine Setup.

3.2.4 Costs

In Sheet B2 the cost setup can be found as in Figure 18.

a) The cost of fuels per kWh can be edited.
b) The installation cost per kW for the specific engine type can be edited.
c) The expected lifetime of the system can be edited.
d) The maintenance cost per kW per year can be edited.
e) The interest rate can be edited.

Price development and investments														
	Disel Variable RPM		Diesel Constan RPM		Diesel Electric		LNG		LNG Electric		Hydrogen		Batteries	
	CAPEX	OPEX	CAPEX	OPEX	CAPEX	OPEX	CAPEX	OPEX	CAPEX	OPEX	CAPEX	OPEX	CAPEX	OPEX
1	13,0	28,53	13,0	29,00	61,2	30,14	43,3	24,82	90,3	24,02	57,4	84,43	307,9	11,43
2	0	28,53	0	29,00	0	30,14	0	24,82	0	24,02	0	84,43	0	11,43
3	0	28,53	0	29,00	0	30,14	0	24,82	0	24,02	0	84,43	0	11,43
4	0	28,53	0	29,00	0	30,14	0	24,82	0	24,02	57,35	84,43	0	11,43
5	0	28,53	0	29,00	0	30,14	0	24,82	0	24,02	0	84,43	0	11,43
6	0	28,53	0	29,00	0	30,14	0	24,82	0	24,02	0	84,43	0	11,43
7	0	28,53	0	29,00	0	30,14	0	24,82	0	24,02	57,35	84,43	0	11,43
8	0	28,53	0	29,00	0	30,14	0	24,82	0	24,02	0	84,43	0	11,43
9	0	28,53	0	29,00	0	30,14	0	24,82	0	24,02	0	84,43	0	11,43
10	0	28,53	0	29,00	0	30,14	0	24,82	0	24,02	57,35	84,43	0	11,43
11	0	28,53	0	29,00	48,2328	30,14	0	24,82	46,9393	24,02	0	84,43	307,853	11,43
12	0	28,53	0	29,00	0	30,14	0	24,82	0	24,02	0	84,43	0	11,43
13	0	28,53	0	29,00	0	30,14	0	24,82	0	24,02	57,35	84,43	0	11,43
14	0	28,53	0	29,00	0	30,14	0	24,82	0	24,02	0	84,43	0	11,43
15	0	28,53	0	29,00	0	30,14	0	24,82	0	24,02	0	84,43	0	11,43
16	0	28,53	0	29,00	0	30,14	0	24,82	0	24,02	57,35	84,43	0	11,43
17	0	28,53	0	29,00	0	30,14	0	24,82	0	24,02	0	84,43	0	11,43
18	0	28,53	0	29,00	0	30,14	0	24,82	0	24,02	0	84,43	0	11,43
19	0	28,53	0	29,00	0	30,14	0	24,82	0	24,02	57,35	84,43	0	11,43
20	0	28,53	0	29,00	0	30,14	0	24,82	0	24,02	0	84,43	0	11,43
Costs	314,349		319,325		399,4111		303,412		361,14		1115,77		555,094	



	Average price	NOK		NOK		MNOK		NOK
MGO	Price per kWh	0,58	Price per kW	3000	Lifetime	20	Maintenance per year per kW	0
LNG	Price per kWh	0,58	Price per kW	10000	Lifetime	20	Maintenance per year per kW	0
Hydrogen	Price per kWh	2,28	Price per kW	13000	Lifetime	3,00	Maintenance per year per kW	0
Batteries	Price per kWh	0,57	Price per kWh	5460	Lifetime	10,00	laintenance per year per kWh	0

Interest	7 %

Figure 18 Cost Setups in Sheet G.

3.3 Passenger Vessel

The first advanced setups are ship design. Then Route studies and engine setup. In the end, costs can be edited.

3.3.1 Ship Design

In Sheet B2 the ship design input can be found as in Figure 19. In sheet D the admiralty curve is illustrated graphically, and the main dimensions are listed as shown in Figure 20.

a) If wanted, the power-speed curve setting can be changed from "Automatic" to "Manual". Then the values for the power-speed curve will have to be added manually. The power-speed curve can also be changed by editing "design-speed" and "design-speed-power" in sheet B2. By doing this, the admiralty method is used to estimate a power-speed curve.
b) Dimensions can be added. If deadweight and lightweight are added, the additional resistance by use of batteries are added to the power-speed curve.
c) Operational loads can be changed if wanted.

Ship Design

Ship Power Speed Curve setting: Automatic

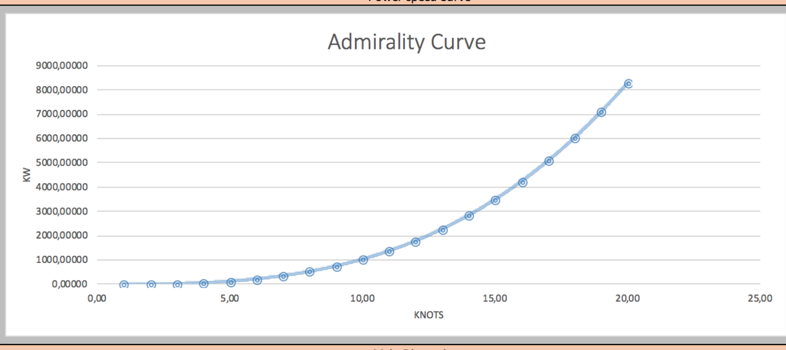
	constant	x	x^2	x^3	x^4	x^5	x^6
Ship-Power Curve	-9E-13	4E-13	-3E-14	1E+00			

	L_{OA}	L_{PP}	L_{WL}	Breadth	Draft	Deadwgt.	Lightwgt	Ballast	Service Area
Dimensions	125	na	na	20	0	na	na	na	2

	Harbour	Entering harbour	Leaving Harbour	Acceleration	Passive retardation	Active retardation
Operational Loads	0	1500,00	1500,00	4000	1000	1500

Figure 19 Ship Design inputs in Sheet B2.

Power-speed Curve



Main Dimensions

	L_{OA}	L_{PP}	L_{WL}	Breadth	Draught	Deadwgt.	Lightwgt	Ballast	Service Area
Dimensions	125	na	na	20	0	na	na	na	2

Figure 20 In Sheet D the Admiralty Curve is graphically presented and the main dimensions are listed.

3.3.2 Route Studies

In Sheet B2 the route study inputs can be found as in Figure 21. In sheet D the Route Presentations and editable values for capability and sea margins are found as in Figure 22.

a) Design-speed is described in section 3.1.1.
b) The time necessary for the different maneuvering operations can be edited if necessary.
c) The design max speed is used to estimate the maximum engine size. It can be edited if necessary.

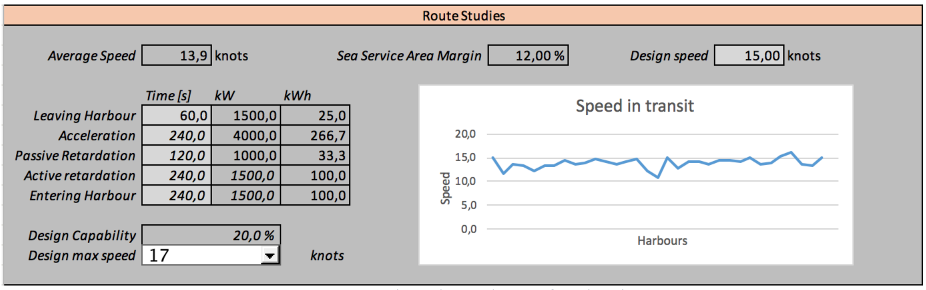


Figure 21 Route Studies Advanced inputs found in Sheet B2.

The purpose of the graphical illustration of route studies in sheet E (shown in Figure 22) is to illustrate what the ship is being used for, and which modes that are using most energy.

Capabilites and Sea Margin

Capabilites	
Level	%
1	20
2	40
3	70
4	100

Sea Margin	
Level	%
1	5
2	12
3	18
4	40

Figure 22 Route Presentations and editable values for capability and sea margins can be found in Sheet E.

3.3.3 Engine Setup

In Sheet B2 the engine setup can be found as in Figure 23. In sheet E, more settings for engine configurations can be found. Sheet E is presented in Figure 24.

Figure 23:

a) Design Speed Power are described in section 3.1.1
b) Max Power is the calculated maximum power necessary to run the ship. This is predefined and is recommended not changed unless the user has a specific value to use.
c) Hotel power is set to 750 kW but is editable if wanted.
d) Component losses can be edited.
e) Battery lifetime can be edited if wanted

f) If the user wants to add one component that is not included in the tool, “Open” can be changed. The representative component loss has to be added.
g) The “Power Only for propulsion”-input defines how much of the energy that is used for propulsion for the different operations. The different operations are described in “Ship Design”.
h) Emission-factors can be edited.

Engine Setup

Max Power	*7306,2*	*kW*		*Battery lifetime*	*10*	*years*
Design Speed Power	*3500*	*kW*		*Hotel Load*	*750*	*kW*

	Generator	*Drives/Converter*	*DC/DC Converters*	*Switchboard*	*El-motors*	*Gear*	*Cabling*	*Open*
Losses	*5 %*	*5 %*	*5 %*	*3 %*	*5,9 %*	*5 %*	*3 %*	*0 %*

Emissions

	CO_2 per kg fuel, kg	*Nox per kWh, g*	*CO per kWh, g*	*PM per kWh, g*	*SO per kWh, g*
Diesel Variable RPM	*3,17*	*7,85*	*5*	*0,5*	*1*
Diesel Constant RPM	*3,17*	*7,85*	*5*	*0,5*	*1*
LNG Constant RPM	*2,76*	*1,5*	*0,05*	*0,005*	*0,01*

Figure 23 Engine Setup in Sheet B1.

Figure 24:

a) Efficiency losses for propulsion and electricity can be activated or deactivated. Indicators underneath shows the representative efficiency of the powertrain (excluding the engine).
b) Manual Engine load-curves can be added for fossil fuel engines under "Efficiency, Fossil fuels".
c) The expected lifetime of a fuel cell can be changed in "Hours of operation".
d) The design stack power can be edited under "Design Stack Size".
e) The Peak power efficiency can be edited. This is the power that the stack delivers when it is running at peak efficiency.
f) The peak efficiency can be edited.
g) The efficiency curve describing the efficiency from peak and forward can be edited.
h) The design lifetime of batteries can be edited.
i) The carbon footprint by production, transport and storage of LNG, Diesel and electricity (Norwegian mix) can be edited.
j) The well-to-wheel efficiency can be added.

Efficiency, propulsion

	Diesel Var	Diesel const	Diesel-Battery	LNG Const	LNG-Battery	Batteries	Hydrogen
Generator	no	no	yes	yes	yes	no	no
Drives/Converter	no	no	yes	yes	yes	yes	yes
Cabling	no	no	yes	yes	yes	yes	yes
Switchboard	no	no	yes	yes	yes	yes	yes
El-motors	no	no	yes	yes	yes	yes	yes
DC/DC converters	no	no	no	no	no	no	yes
Gear	yes	yes	yes	yes	yes	yes	yes
Overall	95,00 %	95,00 %	75,91 %	75,91 %	75,91 %	79,91 %	75,91 %

Efficiency, electricity production

	Diesel Var	Diesel const	Diesel-Battery	LNG Const	LNG-Battery	Batteries	Hydrogen
Generator	yes	yes	yes	yes	yes	yes	yes
Drives/converter	yes	yes	yes	yes	yes	yes	yes
Cabling	yes	yes	yes	yes	yes	yes	yes
Switchboard	yes	yes	yes	yes	yes	yes	yes
DC/DC Converters	no	no	no	no	no	no	yes
Open	no	no	no	no	no	no	no
Overall	84,92 %	84,92 %	84,92 %	84,92 %	84,92 %	84,92 %	80,67 %

Efficiency, fossile fuels

	Const	x	x^2	x^3	x^4	x^5	x^6
iesel Variable RPM	0,3099	0,58	-4,0844	15,441	-29,665	27,841	-10,15
esel Constant RPM	0,1667	1,1482	-3,1976	5,072	-4,1771	1,3626	
LNG	0,1406	1,7576	-3,8877	#######	-1,56E+00		

Efficiency, electricity production, Hydrogen

Max power	6720,00		Number of cells	56,00	54,00 % until 1960 kW
Hours of operation	25000	h	'eak Efficiency kW	35	
Design lifetime	4,00	years	Weight	20160	kg
Design Stack Size	120	kW	Cost cell:	87,36	MNOK

From max efficiency to mac performance

const	x	x^2	x^3	x^4
0,44	0,84	-2,54	2,96	-1,25

Efficiency, electricity production, Batteries

			Cost	27,49	MNOK
			Design Capacity	5034,77	kWh
Cycluses	3031,56		*Number of stacks*	37,13	Stacks
Allowed discharge	80%	%	*Weight of stacks*	65422,25	kg

Power	2517,38	5034,766	7552,15	10069,5	12586,9	15104,29693
Losses	0,95 %	1,75 %	2,55 %	3,50 %	4,30 %	5,25 %

inutes in harbour for charging	5,00	min
	480	max
Is batteries possible with the current setup?	No	

Carbon footprint and well to wheel efficiency fromproduction

	CO2-equivalents per kg fuel, g	Well to wheel efficiency %
Diesel variable rpm	*397,22*	
LNG	*407,84*	
Electricity, Norwegian mix	50	

Figure 24 Sheet E - Engine Setup.

3.3.4 Costs

In Sheet B2 the cost setup can be found as in Figure 25.

a) The cost of fuels per kWh can be edited.
b) The installation cost per kW for the specific engine type can be edited.
c) The expected lifetime of the system can be edited.
d) The maintenance cost per kW per year can be edited.
e) The interest rate can be edited.

Price development and investments

	Disel Variable RPM		Diesel Constan RPM		Diesel Electric		LNG		LNG Electric		Hydrogen		Batteries	
	CAPEX	OPEX	CAPEX	OPEX	CAPEX	OPEX	CAPEX	OPEX	CAPEX	OPEX	CAPEX	OPEX	CAPEX	OPEX
1	21,9	44,56	21,9	45,80	57,4	52,50	73,1	45,80	108,6	52,50	122,9	157,26	27,5	0,00
2	0	44,56	0	45,80	0	52,50	0	45,80	0	52,50	0	157,26	0	0,00
3	0	44,56	0	45,80	0	52,50	0	45,80	0	52,50	0	157,26	0	0,00
4	0	44,56	0	45,80	0	52,50	0	45,80	0	52,50	0	157,26	0	0,00
5	0	44,56	0	45,80	0	52,50	0	45,80	0	52,50	87,36	157,26	0	0,00
6	0	44,56	0	45,80	0	52,50	0	45,80	0	52,50	0	157,26	0	0,00
7	0	44,56	0	45,80	0	52,50	0	45,80	0	52,50	0	157,26	0	0,00
8	0	44,56	0	45,80	0	52,50	0	45,80	0	52,50	0	157,26	0	0,00
9	0	44,56	0	45,80	0	52,50	0	45,80	0	52,50	87,36	157,26	0	0,00
10	0	44,56	0	45,80	0	52,50	0	45,80	0	52,50	0	157,26	0	0,00
11	0	44,56	0	45,80	35,49	52,50	0	45,80	35,49	52,50	35,49	157,26	27,48982	0,00
12	0	44,56	0	45,80	0	52,50	0	45,80	0	52,50	0	157,26	0	0,00
13	0	44,56	0	45,80	0	52,50	0	45,80	0	52,50	87,36	157,26	0	0,00
14	0	44,56	0	45,80	0	52,50	0	45,80	0	52,50	0	157,26	0	0,00
15	0	44,56	0	45,80	0	52,50	0	45,80	0	52,50	0	157,26	0	0,00
16	0	44,56	0	45,80	0	52,50	0	45,80	0	52,50	0	157,26	0	0,00
17	0	44,56	0	45,80	0	52,50	0	45,80	0	52,50	87,36	157,26	0	0,00
18	0	44,56	0	45,80	0	52,50	0	45,80	0	52,50	0	157,26	0	0,00
19	0	44,56	0	45,80	0	52,50	0	45,80	0	52,50	0	157,26	0	0,00
20	0	44,56	0	45,80	0	52,50	0	45,80	0	52,50	0	157,26	0	0,00
Costs		492,53409		505,64141		626,748303		553,439		674,5459		1971,395252		38,751637

	Average price	NOK		NOK		MNOK		NOK
MGO	Price per kWh	0,58	Price per kW	3000	Lifetime	20	Maintenance per year per kW	0
LNG	Price per kWh	0,58	Price per kW	10000	Lifetime	20	Maintenance per year per kW	0
Hydrogen	Price per kWh	2,28	Price per kW	13000	Lifetime	4,00	Maintenance per year per kW	0
Batteries	Price per kWh	0,57	Price per kWh	5460	Lifetime	10,00	Maintenance per year per kWh	0

Interest 7 %

Figure 25 Cost Setups in Sheet G.

4. Settings and modifications

In this section, several settings and modifications that are requested by users are explained. This document will be updated when new configurations are asked for. For latest update, please send an email to Jorgen.kopperstad@gmail.com.

4.1 Adding vessels to the vessel database

For all versions of the tool, the additional vessels can be added to the vessel database in the Data-sheet in cell-range B2:AI9. Existing vessels can be deleted if necessary.

E. Interviews

Interview 1, 2 and 3 are based on the same questions and completed onboard the Live Fish Carrier NFT Steigen in February 2018. Interview 4 are from Christian Remøy, Chief Officer in Sølvtrans.

Interview 5 and 6 are from Senior Designer Electro in Havyard Design and Solutions Kay Lorgen and Product Manager Michael Odland in Norwegian Electric Systems.

Interview 1

Object: Officer André Lyng

1. During a one-year period. Please suggest 10 operational modes that are significant either because of the amount of time the ship is in that mode or because of the energy consumption during that mode.
   - Cargo operations
   - Transit in nice and bad weather. Full speed and eco speed.
   - Stand by in harbor
   - Entering and leaving harbor
   - Standby with facility
   - Tank wash

2. For the ship-type that you have been asked to represent, please answer the following:

   2.1. What do you think are the three most energy demanding modes?
   - Loaded transit in bad weather.
   - Cargo Operations at summertime when the RSW system is running.

   2.2. What do you think are the three less energy demanding modes?
   - Standby in Harbor
   - Transit unloaded eco
   - Tank wash

   2.3. Do you think there is a significant difference between energy consumption for ships dependent on the officer in charge at the bridge?
   - Yes.

3. Do you feel the pressure for reducing fuel costs and emissions during operation?
   - All crew members have a genuine interest in doing a good job.
   - There are many other considerations for the customer that are more important than the environmental impact of the ship. For example, fish health, safety and more.

4. Do you see potential ways of cutting fuel costs during operation?
   - By increased use of the shaft-generator at the main engine.
   - By decrease of speed during transit.

5. Other comments
   - The ship´s capability is very good. This is impressive and very important for the officer on the bridge. Increased capability leads to improved safety and workability for the ship.
   - It is assumed that the ship uses between 9-11 cubic of fuel for one day.

Interview 2

Object: Captain Kent Sjåvik

1. During a one-year period. Please suggest 10 operational modes that are significant either because of the amount of time the ship is in that mode or because of the energy consumption during that mode.
   - Loading
   - Off-loading
   - Fish-treatment
   - Stand by in harbor
   - Transit, unloaded, 75% load on main engine, 12 knots.
   - Transit, unloaded 90% load on main engine, 13,5-14 knots
   - Transit, loaded, 90% load on main engine, 11 knots
   - Transit, loaded, 70% load on main engine, 8 knots
   - Entering harbor, takes about 15 minutes and 800 kW on main engine
   - Approaching facility, takes about 15 minutes
   - Waiting on facility (only circulations pumps)
   -
2. For the ship-type that you have been asked to represent, please answer the following:
   a. What do you think are the three most energy demanding modes?
   - Transit with cargo
   - Maneuvering
   - Entering and leaving harbor

   b. What do you think are the three less energy demanding modes?
   - Tank wash
   - Waiting on facility
   - Standby in harbor
   -

   c. Do you think there is a significant difference between energy consumption for ships dependent on the officer in charge at the bridge?
   - There is no doubt about that.
   - Some officers are more or less careful, this is very related to weather and experience.

3. Do you feel the pressure for reducing fuel costs and emissions during operation?
   - In this business there is are other factors that are more important for ship owner and customer such as fish health and efficiency.
   -
4. Do you see potential ways of cutting fuel costs during operation?
   - By switching to LED lights onboard.
   - By installing a precise fuel indicator always showing the exact fuel consumption. This can make the crew learn more about the consumption in different operations and therefore make other decisions when this is possible.

Interview 3

Object: Officer Pål Ustad

1. During a one-year period. Please suggest 10 operational modes that are significant either because of the amount of time the ship is in that mode or because of the energy consumption during that mode.
   - Stand by in harbor
   - Transportation of fish, open circulation.
   - Transportation of fish, closed circulation.
   - Lice treatment freshwater
   - Lice treatment hydrogen peroxide.
   - Lice treatment by the medical treatment called salmosan
   - Fish sorting
   - Transit, 10 knots.

2. For the ship-type that you have been asked to represent, please answer the following:
   a. What do you think are the three most energy demanding modes?
   - Lice treatment by freshwater while running the RSW-system.
   - Transit full speed
   - Fish sorting with RSW.

   b. What do you think are the three less energy demanding modes?
   - Transit with fish, open circulation
   - Offloading
   - Transit without fish

   c. Do you think there is a significant difference between energy consumption for ships dependent on the officer in charge at the bridge?
   - Yes.

3. Do you feel the pressure for reducing fuel costs and emissions during operation?
   - No focus at all.
   - Other areas that are more important for this type of vessel.

4. Do you see potential ways of cutting fuel costs during operation?
   - By making the crew more aware of the consumptions and the effect of their choices.
   - Planning

Interview 4

Object: Chief Officer Christian Remøy
Company: Sølvtrans

1. During a one-year period. Please suggest 10 operational modes that are significant either because of the amount of time the ship is in that mode or because of the energy consumption during that mode.

- Standby in harbor (Moored)
- Pulling out (Thrusters enabled)
- Transit without cargo (ECO or FULL)
- Transit with cargo (Oxygen generator, RSW (refrigerated sea water), Circulation pumps)
- Approaching (Facility or harbor / Thrusters enabled)
- Cargo operations (Loading/discharging /delousing)
- Maneuvering (Between docks or within the fish farm)
- Tank wash (At drift /Slow steaming or alongside dock)
- Waiting on facility readiness (Before cargo ops and at drift/ slow steaming)
- Operational STBY (pause in the loading/discharge / Waiting on crew etc.,)

2. For the ship-type that you have been asked to represent, please answer the following:

2.1 What do you think are the three most energy demanding modes?

- Transit with cargo
- Transit without cargo
- Cargo ops

2.2 What do you think are the three less energy demanding modes?

- Standby in harbor
- Waiting on facility
- Operational standby

2.3 Do you think there is a significant difference between energy consumption for ships dependent on the officer in charge at the bridge?

- Yes.

Interview 5

To: Kay Lorgen
Company: Havyard Design & Solutions AS
Case: Losses in ship propulsion

This question form is a part of a master thesis at the University of Bergen. The key problem is efficiency, emissions and costs of different fuel systems for ship designs. This question form will be attached to the master thesis.

Please fill inn expected values for efficiency losses according to industrial standards. Note that losses can be given in intervals (for example 4-7%). Feel free to comment if necessary.

Component	Losses, %	Comments
Generator	Normal 3-5% losses	Depends on load and power factor
Gear		
Cabling	0,4-0,8%	
Switchboard	0,4-1%	AC version.
DC/DC Converters	1,0-1,2%	
Drives	1,5-1,9%	

Interview 6

To: Mikael Odland
Company: Norwegian Electric Systems
Case: Losses in ship propulsion

This question form is a part of a master thesis at the University of Bergen. The key problem is efficiency, emissions and costs of different fuel systems for ship designs. This question form will be attached to the master thesis.

Please fill inn expected values for efficiency losses according to industrial standards. Note that losses can be given in intervals (for example 4-7%). Feel free to comment if necessary.

Component	Losses, %	Comments
Generator	3-5 %	Mechanical loss
Gear	N/A	
Cabling	<1 %	
Switchboard	<1 %	
DC/DC Converters	2-3 %	Including filter loss
Drives	3-4 %	Including filter loss

F. Programming Software

In the early stage of the project, several programs for designing the tool were evaluated. Common tools as *Matlab*, *Excel*, *FORTRAN*, *Java* and others were all compared and evaluated.

One of the key values of the tool is that it was supposed to be simple and possible to use without broader understanding of energy, efficiency, ships and hydrodynamics. To do this, all inputs and outputs have to be self-explanatory, the tool simple to use and possible to adjust for other purposes. In addition, the software necessary for using the tool and the applicability of the software had to be carefully considered.

The matrix used to evaluate the chosen considered programs and coding languages are shown in Table 23. All numbers are based on evaluations done by the student and the student only.

Matlab, *Octave* and *C++* achieved the lowest score of the seven candidates. *Matlab* mainly ended up in this group because of the price of the software. It is widely used, but mainly for research and education purposes compared to more common software. *Octave* has issues being applicable for this purpose alone, and the graphics are poor. *C++* demands broader understanding of programming to handle, and even though it can be used for free, it`s graphical interface and it`s extend is limited.

FORTRAN, Java and *LaTeX* got the 4th, the 3th and the 2th best score in the test. They are all free-to-use software/codes, and both *LaTeX* and *Java* are very applicable for the purpose of the tool. The reason why they didn`t achieve the highest score, were that they only score average in ease of use, graphics and extend.

The reason why excel has been chosen as the GUI (Graphical User Interface), is that the price of an office-license for a user is small, it is common and easy to use. The graphics are easy understandable. A drawback is that the applicability is limited. Feeding big amount of data into an excel datasheet is a complex operation, and the user interfaces of the program code are limited. Since the purpose of the tool is to develop an understandable and usable tool, Excel anyhow gets the highest score and is therefore the program used in this project.

Table 23 Tool Software Evaluation Matrix.

Software/code	Price	Ease	Graph-ics	Extent	Applic-ability	Total Score
Matlab	1	5	5	8	5	24
Fortran	10	5	5	5	5	30
Java	10	2	5	7	10	34
Excel	7	10	10	8	5	40
Octave	10	3	2	4	2	21
LaTeX	10	5	5	5	10	35
C++	10	3	5	5	5	28

G. Calm Water Performance

In Havyard Design and Solutions, modern simulations tools using CFD simulates the hull in calm water. By doing this, hull resistance curves can be obtained. This information is used to estimate the force needed to move the ship.

The most common way of estimating the power-speed curve is by towing a model of the ship in a test tank. By scaling up the values the power needed to move the ship in a given speed is found.

The calm water performance does not consider waves, current and wind, and therefore, it is an estimate of the hull in ideal sea conditions. The calculations made to produce a power-speed curve is a complex operation based on several steps demanding knowledge in hydrodynamics and fluid flow.

A screenshot of a calm water simulation is shown in Figure 74.

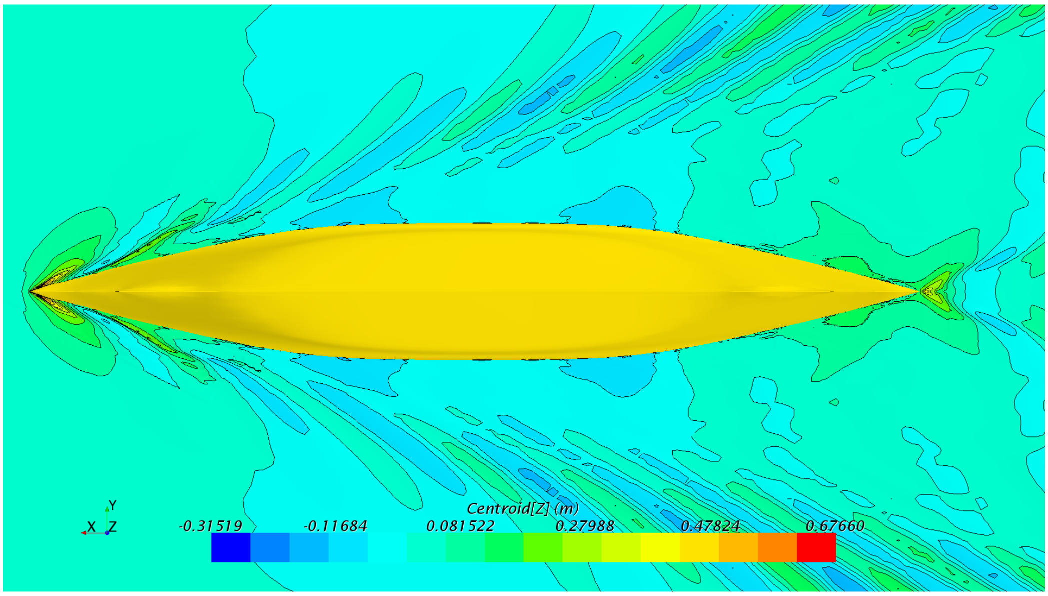


Figure 74 Calm Water performance in C++.

H. Ship Size Parameters

To describe a ship's carrying capacity, *deadweight*, *lightweight* and *displacement* are the most common explanatory variables. The Displacement equals the ships lightweight and deadweight and represents the amount of water displaced by the ship. The standard measure for this is normally done in seawater with a mass density of 1.025 t/m^3.

Lightweight of the ship is used to indicate the size of the ship. This is the displacement part that is represented by the ship hull, power systems, hotel and equipment. The *deadweight* is used to indicate the ships carrying capacity and is represented by the loaded capacity including bunkers and others supplies necessary for the ship's propulsion [12]. The relation between *deadweight*, *lightweight* and *displacement* can be described as in Formula 45

Formula 45 Relation between deadweight, lightweight and displacement.

$$deadweight = displacement - lightweight$$

a. *Description of hull forms*

Since the density of water is higher than the density of air, it is logical that the part of the hull that is under water is more important for the ship resistance in water than the part above water. There are three main factors to describe the length of a hull:

- Length over all, L_{OA}
- Length between perpendiculars, L_{PP}
- Length of waterline, L_{WL}

There are several measures for a ships draught in water:

- Draught, D
- Breadth of waterline, B_{WL}
- Midship Section area, A_M

The factors described above can all be found in Figure 75.

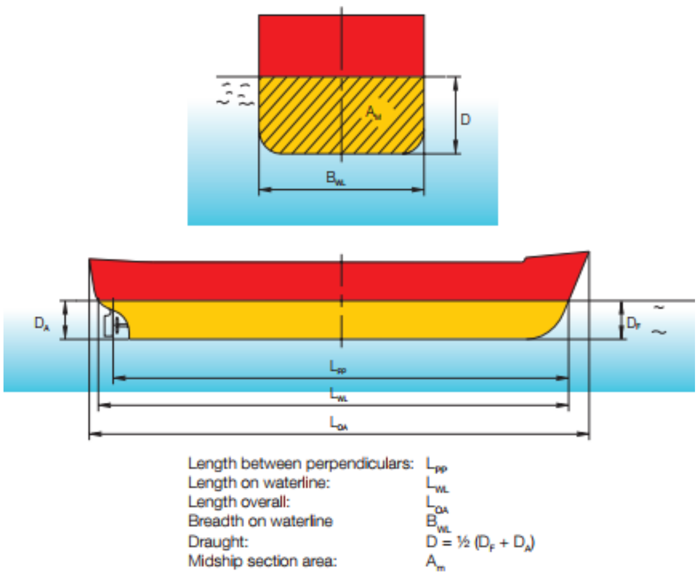


Figure 75 Factors for ship hull dimensions. [12]

Since the part of the hull that is acting is water is the most relevant for dimensioning the ship power train, L_{OA} is considered to be less relevant than L_{PP} and L_{WL}. The length between perpendiculars can be described as the distance between the point where the bow section enters water and the center of the rudder. Length of waterline is the distance from the ends of the hull where the hull enters water.

B_{WL} represents the breadth of the ship at the longitudinal point where the breadth is maximum. A_M is the area of the front view of the hull in water. Draught, D, is the vertical distance from the waterline to the point of the hull that is deepest.

b. Block Coefficient, C_B

The *Block Coefficient, C_B,* has for decades been an important measure of a ships hydrodynamic capabilities. C_B can express the shape of the hull since it is defined as the ratio between the displacement volume ∇ and the volume of squared box if we only consider draught, L_{PP} and B_{WL}. C_B can be expressed as in Formula 46.

Formula 46 Block Coefficient, C_B. [12]

$$C_{B,WL} = \frac{\nabla}{L_{PP} \cdot B_{WL} \cdot D}$$

To find the variation in the block coefficient C_B as a function of draught, MAN use a formula to relate the new block coefficient with the design coefficient ($C_{B,\,des}$, D_{des}). This can be found in Formula 47.

Formula 47 New C_B function. [12]

$$C_B = 1 - (1 - C_{Bdes}) \cdot \left(\frac{D_{des}}{D}\right)^{\frac{1}{3}}$$

Further, the new displacement as a function of draught can be found as in Formula 48.

Formula 48 New ∇ function. [12]

$$\nabla = \frac{C_B}{C_{Bdes}} \cdot \frac{D}{D_{des}} \cdot \nabla_{des}$$

The block coefficient of a floating lighter may be as high as 0.9, while it for a ferry boat or a container ship may be as low as 0.5. [12]

c. Water Plane Area Coefficient, C_{WL}

Another factor that can be used to describe hull properties is the water plane area coefficient that relates the water waterline area to the product of the length (L_{WL}) and the breadth (B_{WL}) of the ship. The waterline area is the horizontal area of the hull entering the water.

The coefficient indicates the acuteness of the hull. In general, C_{WL} is 0.1 higher than C_B.

d. Midship section coefficient, C_M

To describe the relation between the immersed transverse ship area and the B_{WL} and D, the midship section coefficient C_M can be used. This is in general much higher than both C_B and C_{WL} due to several factors such as loading capacity and stability. [12]

I. Waves

In this section, *"Linear Wave Theory"* by Harald E. Krogstad et. Al [62] has been used as a reference. Wave theory in general will be introduced for the concerned reader. This is presented to introduce the reader to the most common variables in wave spectrum simulations and the dependent explanatory response variables.

Waves are difficult to present mathematically. A regular sinus wave is a theoretical wave rarely found in practice. To use mathematical descriptions to evaluate a wave spectrum of a given ocean state demands simplifications. By measuring the average amplitude, wavelength and period different theoretical wave spectrums can be used to discuss the energy transfer in an ocean wave and this can be used to evaluate the energy needed to run the ship through the waves. This more an experience-based method than a theoretical procedure.

a. Wave theory in general

A *regular wave* can be defined by a sine or cosine function. A wave is defined by its amplitude, a wavelength and period. To be fully described, a propagation direction and a phase at a given location and time, also has to be specified. [62] Symbols for the given parameters are listed inTable 24.

Table 24 Parameters for wave spectrums.

Specification	Amplitude	Wavelength	Period
Symbol	A	λ	T

The wavenumber is defined as 2π / λ and can be denoted by the letter *k*. To describe the angular frequency, denoted by ω, the function 2π / T is used. The frequency, *f =1 / T*, is measured in Hertz, Hz.

i. Laplace Equation

To define a surface wave motion, simplifications has to be made. By assuming that water is incompressible, the equation of continuity in Formula 49 is given. Flow in all three directions has to equal zero.

Formula 49 equation of continuity.

$$\frac{\partial u}{\partial x} + \frac{\partial v}{\partial y} + \frac{\partial w}{\partial z} = 0$$

Assuming also that the velocity in y-direction is zero, v is also zero. The so-called velocity potential, Φ, is defined in Formula 50, Formula 51 and Formula 52 for x-, y- and z-direction

Formula 50 Velocity potential, x-direction.

$$u = \frac{\partial \Phi}{\partial x}$$

Formula 51 Velocity potential, y-direction.

$$v = \frac{\partial \Phi}{\partial y}$$

Formula 52 Velocity potential, z-direction.

$$w = \frac{\partial \Phi}{\partial z}$$

Since it is assumed that the speed in y-direction (v) is zero, we obtain the *Laplace Equation* as given in Formula 53.

Formula 53 Laplace Equation.

$$\frac{\partial^2 \Phi}{\partial x^2} + \frac{\partial^2 \Phi}{\partial z^2} = 0$$

ii. Zero motion through the ocean floor

To specify a wave motion, a boundary condition stating that no fluid is moving through the ocean floor can be written as in Formula 54.

Formula 54 Velocity Potential through the ocean floor.

$$w(x, z = -h, t) = \frac{\partial \Phi}{\partial z}(x, z = -h, t) = 0$$

iii. Kinematic Boundary Condition

Since the same particles at any time is moving among the surface, the surface is always made out of the same particles. This can be explained by showing that it is the same particle that moves from A to B. The point at $(x_1, \eta(x_1, t_1))$ is the same as in $(x_2, \eta(x_2, t_2))$ after moving from A to B with the velocity v at time $\Delta t = t_2 - t_1$. Thus we can write Formula 55.

Formula 55 Motion of a fluid point at the free surface.

$$\eta(x_2, t_2) = \eta(x_1, t_1) + w \cdot (t_2 - t_1),\ x_2 = x_1 + u \cdot (t_2 - t_1)$$

Formula 55 can further be explained through Taylor series as in Formula 56.

Formula 56 Motion of a fluid point at the free surface in Taylor series.

$$\eta(x_2, t_2) = \eta(x_1, t_2) + \frac{\partial \eta}{\partial x}(x_1, t_2)((x_2, x_1) + \cdots$$

If Formula 56 is divided by the time specter and we assume that $t_2 \rightarrow t_1$, Formula 57 can be written as:

Formula 57 Kinematic Boundary Condition.

$$\frac{\partial \eta}{\partial t} + u\frac{\partial \eta}{\partial x} = w$$

iv. Dynamic Boundary Condition

At the ocean surface, the pressure must equal the atmospheric pressure. The Bernoulli's equation (Formula 58) can once again be used. $C(t)$ is less important and can be set into an arbitrary convenient constant by assuming $C(t) = p_{atm}/\rho$. This leads to Formula 59.

Formula 58 Bernoulli's Equation.

$$\frac{p}{\rho} + \frac{\partial \Phi}{\partial t} + \frac{1}{2}(u^2 + w^2) + gz = C(t)$$

Formula 59 Bernoulli's Equation with the arbitrary constant.

$$\frac{p}{\rho} + \frac{\partial \Phi}{\partial t} + \frac{1}{2}(u^2 + w^2) + g\eta = 0$$

b. Summary of generalized wave theory

Given the conditions specified in the previous sections, wave spectrums can be defined. There are several modern theories for specifying a wave spectrum. Unlike a wave spectrum defined by a sinus function, an ocean wave is rarely a series of identical waves with equal amplitude, period and wavelength. This makes is more complex to define an ocean wave spectrum, and therefore simplifications has been made to make generalized ocean wave spectrums.

The *Pierson and Moskowitz* and the *JONSWAP (Joint North Sea Wave Project)* wave spectrums are both spectrum relating wave spectral density to wave frequency and wind speed. The *Pierson and Moskowitz* spectrum defines the spectrum for fully developed ocean waves, while JONSWAP states that no wave spectrums are fully developed and therefore in addition added an extra peak enhancement factor. The Pierson Moskowitz wave spectrum are shown in Figure 76. [63]

The different wave spectrums can be used to give an estimate of the energy density of a wave during a given condition. In most cases, there is a correlation between low frequent waves and strong winds.

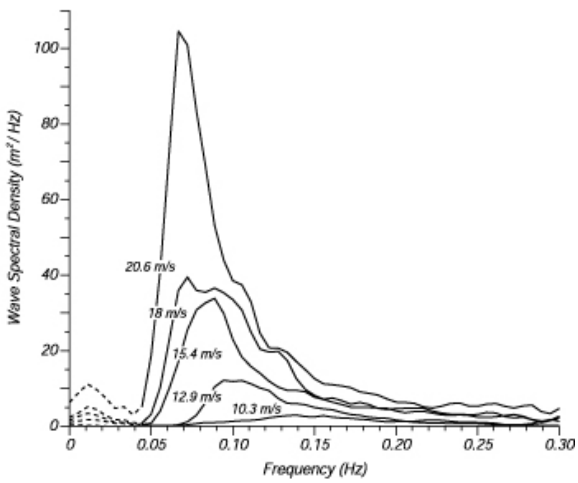


Figure 76 Pierson Moskowitz Wave spectrum. [63]

J. Wind

The part of the ship that is not submerged, are affected by winds. The winds direction plays an important role, since headwind demands more engine to move the ship than tailwind. Side wind can also affects a ships capabilities.

Wind occurs due to mass movements in the atmosphere because of low- and high pressure systems. The rotational Coriolis force also affects the wind speed and direction. Due to friction between the ocean surface and the wind, the wind speed at the surface is zero, and increases with height. The increase is dependent on the air temperature, as shown in Figure 77.

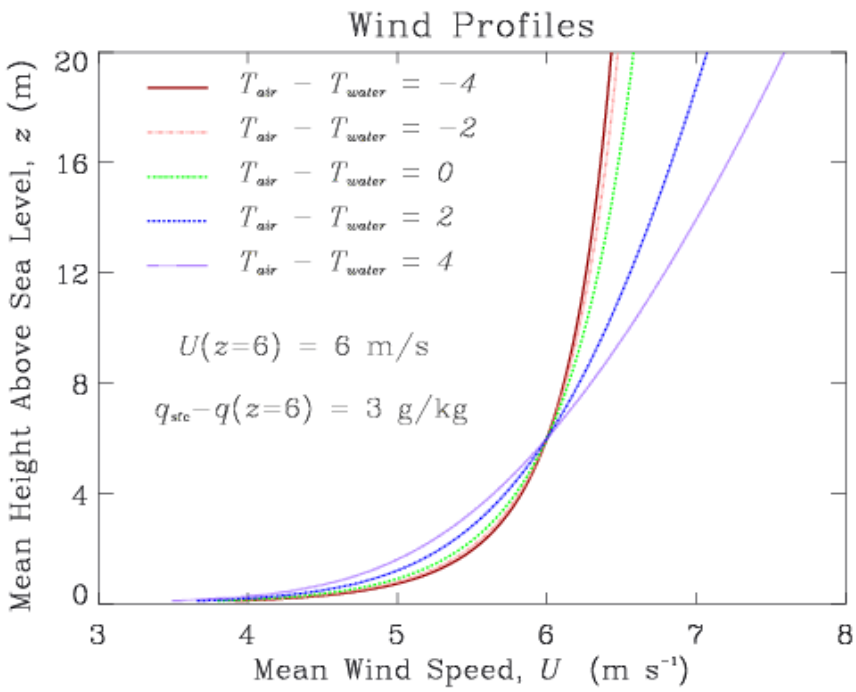


Figure 77 Wind speed from Sea Level [64]

When using winds as criteria for a ship design, it is important to know the difference between average wind speed, gusts and squalls. *Average wind speed*, which is most common in weather forecasts are the average wind measured over a given time. This is valuable when determining how much additional energy that has to be added to the energy consumption analysis. *Wind squalls* are stronger winds than the average wind speed naturally occurring over a minute or more. *Wind gusts* are short period of strong winds, which in many cases can be way much stronger than both squalls and the average wind speed. To insure sufficient capability for a ship, wind gusts are important to consider.

K. Current

Both wind and current are strictly dependent on the atmospheric movements and the Coriolis force. In the northern hemisphere, the Coriolis force is moving the water to the right. If the wind is blowing from north to south, as in Figure 78, the Coriolis force will draw the wind to the right while the friction between the moving air masses (wind) and the sea surface will lead to a speed southbound. In Figure 79, we can see the opposite phenomena, where the wind heading northbound will lead to downwelling. [47]

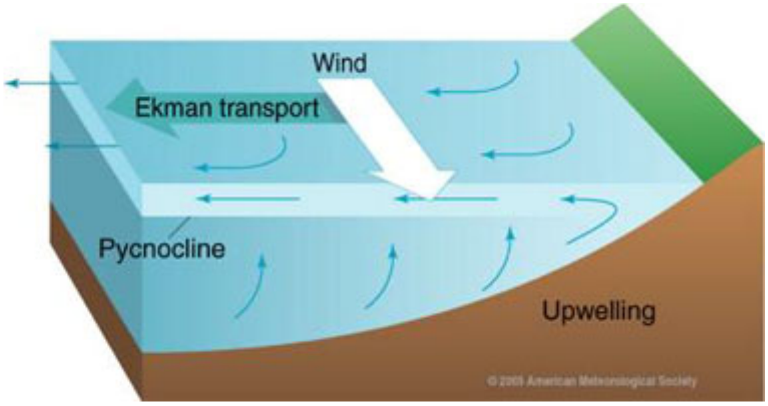


Figure 78 Upwelling [47]

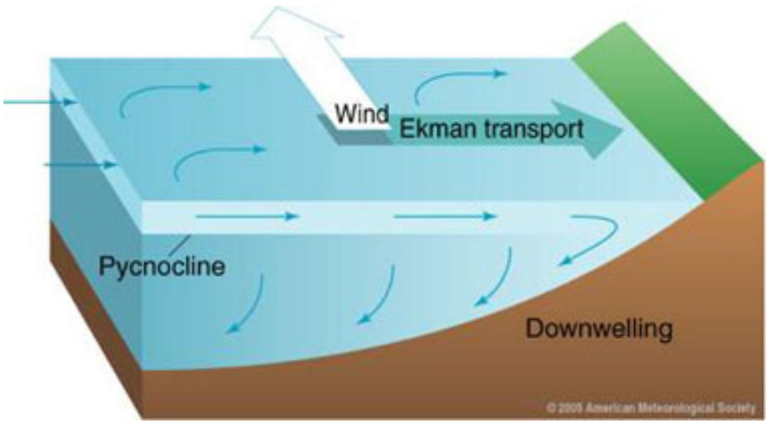


Figure 79 Downwelling. [47]

In ocean fjords, currents are strongly dependent on the precipitation (P), the river runoff (R) and the evaporation (E). By using conservation of volume principles, it can be shown that transport of mass occurs, as in Formula 60. Note that A in this formula represents the area of evaporation or the area of precipitation.

$$V_i + R + AP = V_0 + AE$$

Formula 60 Conservation of volume. [47]

Since salt water has a higher density than fresh water (1025 kg/m^3 vs 1000 kg/m^3), down welling will occur if net P and net R are less than E. The black sea is traditionally an example of a fjord with less precipitation and river run-off than evaporation. A fjord with this continuity pattern is called a *positive* fjord and the bottom layer of the fjord has a net current flowing from the outside and in.

A fjord with negative characteristics have more river run-off and precipitation than evaporation. This leads to a layer of freshwater in the upper layer of the fjord. Since this water is lighter than the heavier salt water underneath, and by using the continuous volume equation, the direction of the current in the upper layer has to point out of the fjord. This is illustrated in Figure 80.

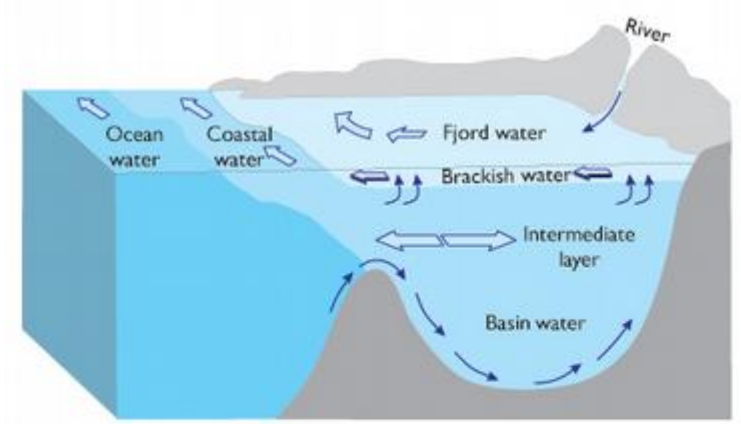


Figure 80 Characteristics of a negative fjord with upper layer current leading out of the fjord. [47]

Since water is heavier than air, the friction is higher for an object in water than in air. For a ship moving from A to B, the wind speed is in most cases stronger than the ocean currents. Anyhow, strong winds often lead to stronger currents, as shown in the previous paragraphs.